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Master project

Refurbishment of Existing Envelopes in Residential Buildings: assessing robust solutions for future climate change

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Contents

List of Figures

List of Tables

Introduction

Evaluating the energy consumption of different design solutions during the design process is essential to reach energy targets. Conventionally, building energy performance is evaluated with energy simulations using a single input weather file (design or typical year) referring only to present weather conditions. Recent works, for example by Gaterell at al. for sites in the United Kingdom, suggest, however, that it is necessary to also include weather files describing climate conditions in future years. That is, the effect of predicted climate change on building performance. Buildings have a life span of 50 to 100 years and so must perform satisfactorily under both current and future climate, adjusting to take advantage of opportunities and to moderate potential damage caused by a changing climate (Wilde et al. 2008). Given the fact that climate is a singularly stochastic phenomenon and that we cannot predict the weather in future years with complete certainty, weather inputs necessarily have intrinsic uncertainties. Using a single weather file in building simulations, regardless of its source or generative algorithm, could lead to inaccurate energy consumption forecasts, and therefore wrong design decisions. In any case, the development of typical weather files was not always done keeping in mind forecasting, but rather what-if analyses.

The innovation in our study consists in the introduction of more than one input weather file in building simulation to represent both present and future years. Our methodology aims to assess the robustness of different design solutions over many possible future climate projections, i.e. the sensitivity of a design or device to uncertain climatic outcomes. We focus on the robustness of refurbishment measures compared to the robustness of the non-refurbished building. We assess each intervention in terms of energy consumption. We decided to focus on existing buildings since they represent the biggest opportunity to reach energy targets today in Europe. In fact, the majority of the European building stock was constructed before any energy regulations and tends to perform poorly for energy consumption and comfort. We propose three indices to make comparisons between refurbishments. The Robustness Index (RI) compares the robustness of the each solution in terms of its range of energy usage. The Energy Saving Index (ESI) assesses the refurbished models in terms of energy usage difference in comparison with the non-refurbished model or base-case. The Gather Index (GI) summarizes the results of the two previous indices to compare the performance of the different refurbishments in terms of both robustness and energy efficiency.

As a case study, we evaluated the robustness of an existing dwelling with twenty-two realistic refurbishments in Turin, Italy. The retrofit solutions focus on the thermal properties of the envelope by varying the U-value, the solar heat gains, the thermal mass and the air tightness of the envelope.

The main outcome of our study is that interpreting numerical simulations of future energy consumption based on single-point estimates of input/output data (i.e. one typical weather file) is risky. Results are better treated as being probabilistic rather than deterministic, as is the norm today. Discussing outcomes in terms of ranges instead of single values improves estimates of outcomes, making it possible to identify robust design solutions for policy and investment decisions.

Sensitivity Analysis in Building Simulation

The starting point of our study is *Sensitivity Analysis* (SA) in building simulation. A sensitivity analysis is the study of how the uncertainty in the output of a mathematical model or system (numerical or otherwise) can be apportioned to different sources of uncertainty in its inputs (Saltelli et al. 2004; Lomas and Eppel 1992). At the building level it allows engineers and architects to assess different design solution by evaluating the effects and sources of uncertainties, in the interest of building robust models. In other words, SA is an informative approach to assess the robustness of design decisions in relation to energy consumption and comfort in the presence of uncertainty (Attia et al. 2012). Sensitivity analysis enriches a simple evaluation since it makes available a range of values rather than a single point. This allows a more complete analysis, verifying both positive and negative scenarios. According to the results of the sensitivity analysis, a design decision is supported in relation to the possibilities of the parameter range.

There are different techniques to conduct SA and to analyse the provided output (Saltelli et al. 2004). “Core techniques” include local and global methods, Monte Carlo and linear regression, screening methods and variance based methods (Hopfe 2009).

Sensitivity analysis are part of many ongoing research activities. For instance the work of Rastogi et al. (2013) investigates the roles of climate change uncertainties in building performances, Lomas at al. (1992) study different techniques of SA for building thermal simulation programs, Lam et al. (1996) examine the sensitivity of energy performance of office buildings in Hong Kong, Attia et al. (2012) create a tool which includes sensitivity analysis to facilitate decision making of zero energy buildings, Hopfe at al. (2009) investigate uncertainty and sensitivity analysis in detailed design support. A sensitive analysis to user behaviour in building performance assessment was done by Hoes at al. (2009) and by Blight et al. (2013) for the energy consumption of passive house dwellings.

Our study is similar to the work of Tian and de Wilde (2011), which focuses on uncertainty and sensitivity analysis of building performance using probabilistic climate projections. In particular they assess the adaptability and resilience of buildings to changing climate conditions by taking into account the uncertainties related to interventions in building fabric and systems as well. They use two sensitivity analysis methods (belonging to the global sensitivity analysis type), SRC (Standardised Regression Coefficients) and ACOSSO (Adaptive COmponent Selection and Smoothing Operator) to determine the key variables affecting simulation outcomes. Their analysis refers to 2050s and three emission scenarios in comparison between each other and the baseline time period. For every emission scenario and the baseline period they used 100 weather files for a total number of 400 EPW weather files used. Their study refers to the thermal performance of the Roland Levinsky Building –in the United Kingdom space– and is divided in three parts. The first one deals with the uncertainties in predicted heating energy, cooling energy and greenhouse gas emissions due to a changing climate only. The second sections adds the complexity of interventions in the building, taking into account uncertainties in weather conditions. The third and final part illustrates a sensitivity analysis that identifies the most important factors that affect the thermal performance of the Roland Levinsky Building.

In our analysis we started from their main conclusion that *the use of multiple weather files is important in quantifying the uncertainties in the prediction of the future performance of buildings* to obtain more reliable results during the design process. By looking at their results we saw that the three scenarios that they analysed did not produce very different results. Considering the fact that we do not use the same amount of weather files, we decided to use more future years and the three different scenarios all in the same analysis. Another difference between the two studies is that we did not use any sensitivity analysis method, while they did. Instead, starting from the same idea of "ranges" of results, we developed three indices to understand and explain the graphs referring to robustness and energy saving. Our methodology is focused on the comparison of different refurbishment solutions by using ranges of data, while their methodology concentrates on the in the evaluation of which variable most influences the energy consumption of a building (the changing climate, or the variation of some building properties). Moreover, we undertook the same analysis in different locations while they focused just on UK. In conclusion, our study concentrates on the development of a methodology that could be useful in the design process. We tested refurbishment solutions and passive measures on the envelope but the same methodology could be applied to other solutions (e.g. new building, active measures).

In the following chapters, after the explanation of our methodology, we will analyse the differences and similarities (if any) with the work of Tian and de Wilde.

Chapter 1

Climate Change

This chapter addresses the main aspects related to climate change and its interaction with buildings. Being able to calculate the impact that these changes have on the energy consumption of buildings is essential for policy and investment decisions. In order to do that is necessary to understand and include the uncertainties that affects building simulations, with respect to climate change. Due to these uncertainties, numerical simulations of future energy consumptions cannot be interpreted based on single-point estimate of input (and, therefore, output) data.

Building simulation and climate related uncertainties are the starting points of this study.

1.1 A general introduction to Climate Change

In 1988, the Intergovernmental Panel on Climate Change (IPCC) was established by the World Meteorological Organization (WMO) and by the United Nations Environment Program (UNEP). This represented an effort by the United Nations for spreading a clear scientific view of the state of the art on human-induced climate change and its potential environmental impacts in the future (Weart 2014). This scientific intergovernmental body does not carry out any research, nor does it control data or climatic parameters. Its objective is to review and assess the most recent scientific, technical and socio-economic literatures produced worldwide for the understanding of climate change, and to gather all the information in reports (IPCC 1998). This is performed through the so-called Assessment Reports, that are composed by Working Groups (WG) and Synthesis Reports (SYR). Currently, the fifth edition of this report (following the earlier assessment reports in 1990, 1995, 2001 and 2007) entitled 'Climate Change 2013' is available only as a preliminary version containing only the first Working Group Report (WG1). There are some compelling evidences outlined in these reports. The first one is the indisputable warming of the climate. The second is about the observed increase in global average temperatures since the mid-20th century, which is mostly due to man-made emissions

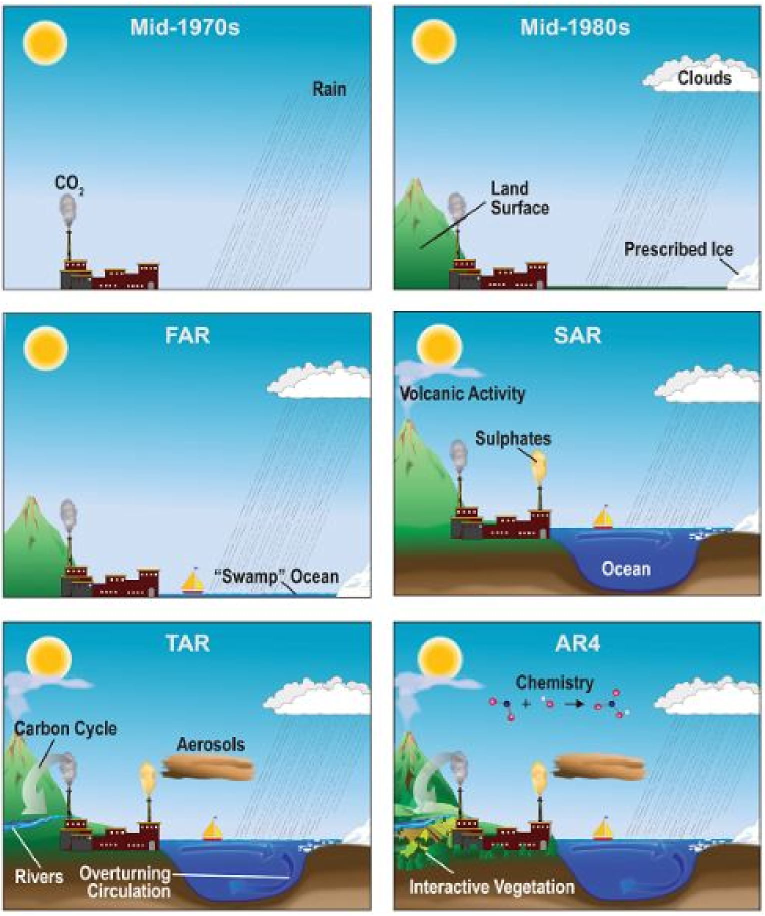


Figure 1.1: The complexity of climate models has increased over the last few decades. IPCC assessment reports: FAR, First Assessment Report (IPCC 1990); SAR, Second Assessment Report (IPCC 1995); TAR, Third Assessment Report (IPCC 2001); AR4, Fourth Assessment Report (IPCC 2007).

of greenhouse gases (GHGs), be them from buildings, business, agriculture or transport (IPCC 2007).

Finally, one of the most relevant conclusion is that, *depending on the strategies of mitigation and adaptation, the extent of climate change effects will diverge over time in different regions*. In fact, there are no certainties over the amount of anthropogenic emissions of greenhouse gases in the future, nor regarding the results of the strategies to reduce them. In any case, even under the most aggressive emission reduction scenarios, global GHGs emissions will continue to grow and *the climate will change anyway* (US EPA 2001).

Several climate models have been developed for the study of the climate in the future, both global (Global Climate Models, GCMs) and regional (Regional Climate Models, RCMs). The climate models are the "virtual laboratory" in which scientists

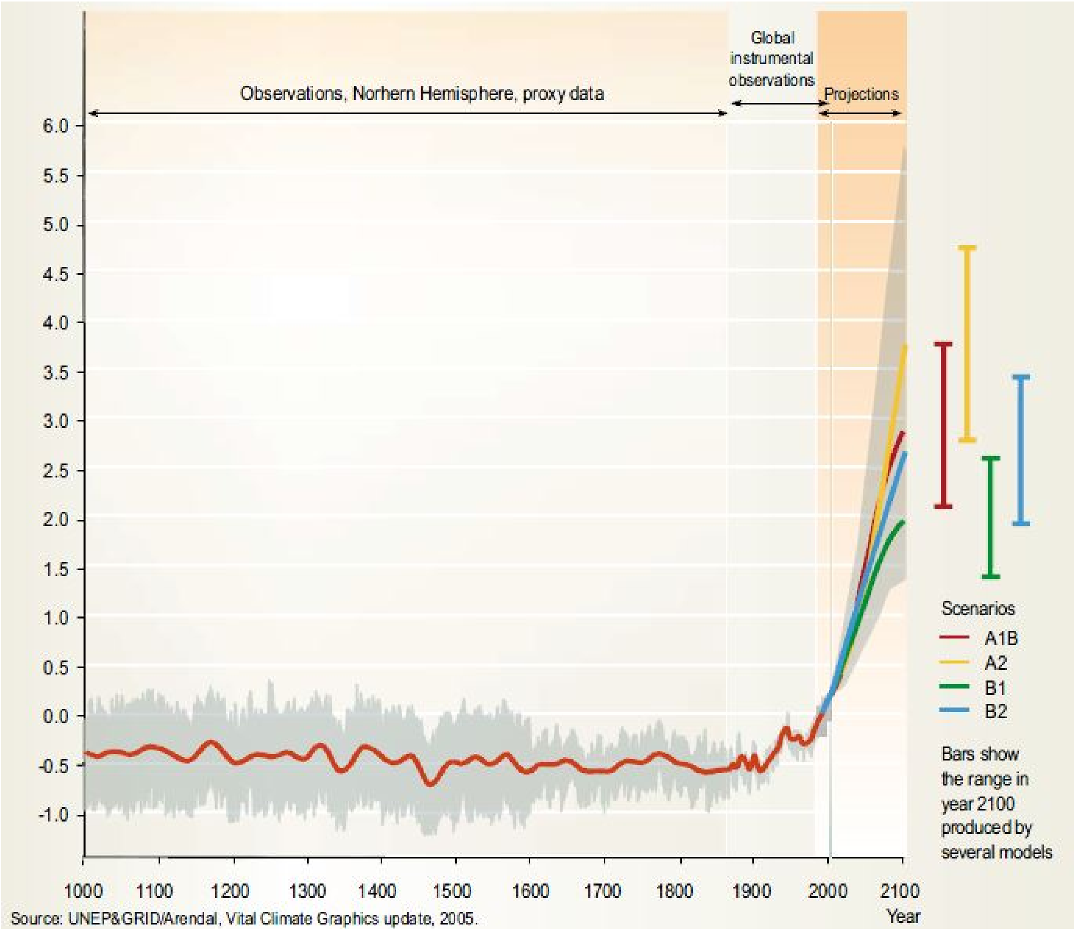


Figure 1.2: Variations in the Earth's surface temperature: year 1000 to 2100 (UNEP 2009).

can simulate the future behaviour of the climate based on past weather data and other measurable variables such as temperature and precipitation (Pasini 2012). Figure 1.1 shows how, over the last 35 years, climate models have been developed and improved by considering more and more components and variables (e.g., atmosphere, carbon cycle, land ice, dynamic vegetation). Therefore, their complexity has increased remarkably (IPCC 2013).

In general, climate models are used to understand the relationship between observed changes in the climate and their likely anthropogenic and natural causes. They are also employed for the development of future climate projections according to established scenarios that are made taking into account future emissions of greenhouse gases and other forcing agents. The final goal of these scenarios is to understand how global climate could change over the next hundred years, taking into account a series of future possibilities (BOM-The Bureau of Meteorology 2013). According to the IPCC AR4

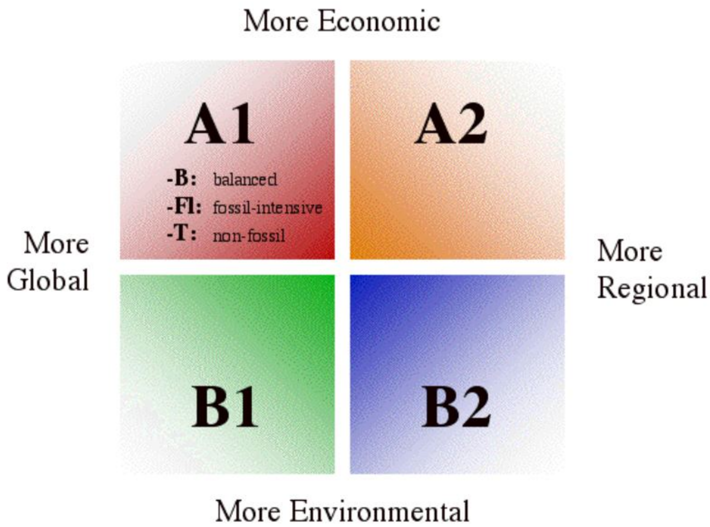


Figure 1.3: Scenarios' families and their storylines (Source: www.meteor.iastate.edu).

> 'a scenario is a plausible and often simplified description of how the future may develop, based on a coherent set of assumptions: a set of working hypotheses about how society may develop, and what this will mean for the climate' (Solomon 2007).

It is not a prediction but a most likely projection as it explains the future by referring to current and past key relationships and driving forces such as population changes, economic development, technological change, energy supply and demand, and land use change. Figure 1.2 compares the Earth's surface temperatures in the past 1000 years with the ones projected in the next 100 years by the aforementioned scenarios. These latter are the ones described in the IPCC Special Report on Emissions Scenarios (SRES) (Nakicenovic and Swart 2000). The 40 future scenarios illustrated in the Report take into account the factors listed above and can be grouped into four scenario families (A1, A2, B1 and B2) (cf. Figure 1.3). These families are characterised by four forces of greenhouse gas emissions, which identify four storylines: more marked oriented, more regional, more environmental and more global. The future worlds, described by the four storylines, vary according to different economic and population growth and technology levels, and describe:

- A1: a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Three A1 groups are defined according to three alternative directions of technological change in the energy system: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).

- A2: a very heterogeneous world. The self-reliance is the most important factor, together with the preservation of local identities. There is a continuous increase of the population and the economic development is primarily regionally oriented. All these factors lead to slower technological developments compared to the other storylines.
- B1: a convergent world with the same global population as in the A1 storyline (with a maximum in mid-century and a subsequent declines), but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. Is given great emphasis to global solutions for economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.
- B2: a world which emphasizes local solutions to economic, social and environmental sustainability, with continuously increasing global population, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines (Nakicenovic and Swart 2000).

No climate initiatives are included in these families, erring on the side of caution. In fact, by considering the effects of the implementation of the Framework Convention of the United Nations for Change Climate Change (UNFCCC) or the emissions targets of the Kyoto Protocol, the future emission scenarios would be much better than the ones expected by the scientists. Another important factor is that the modelled scenarios do not represent the full range of potential climate change impacts, rather they simply describe a range of plausible future climates.

1.2 Climate Change and Building

With respect to the strong evidence that the climate is changing, the United Kingdom government has declared that climate change is the 'greatest long-term environmental challenge' facing the world today (Blair 2004). The built environment is likely to play a critical role in this challenge. First of all, one of the main causes of anthropogenic emission of GHGs is the use of fossil fuel in dwellings (DECC - Department of Energy and Climate Change 2007). For typical developed countries it has been estimated that buildings cause about the 25-40% of the greenhouse gas emissions (Dimoudi and Tompa 2008) as a result of the high energy consumption, especially due to space heating requirements. Secondly, the majority of the building stock in the developed world was constructed before any energy regulations (Gaterell and McEvoy 2005). Strategies which reduce greenhouse gas emissions through measures like an increase in the energy efficiency of the considered systems are known as mitigation strategies. So far, most of the studies connected to the built environment and climate change have been focused on these mitigation measures (Mitchell et al. 2004). On the other hand, buildings have a life span of 50 to 100 years and so must be able to cope with a climate that is going to change in any case. Another approach is, therefore, focused on the reverse relation: building adaptation toward climate change (P. d. Wilde et al. 2008). Only few researches have started to investigate the possible effects that climate change could have on the energy consumption (Lowe 2007; Frank 2005). So far, the overwhelming majority of dwellings were designed for the average climatic conditions prevalent when they were built. Thinking in terms of adaptation, however, *buildings must perform satisfactorily under both current and future climate, adjusting to climate change to take advantage of beneficial opportunities and to moderate potential damage.* However, the interaction between the building system and the external climate is extremely complex and dynamic, involving many variables that are difficult to predict (Guan 2009). An example of this complexity is linked to temperatures. As previously remarked, the global temperature is going to rise with direct consequences on energy consumption. Besides that, this increase could also lead to different distribution of precipitation and therefore of solar and daylight availability. Bioclimatic solutions designed to work with current climatic conditions will likely perform differently under future conditions, with a direct impact on energy consumption. Therefore, *it is necessary to incorporate the potential impacts of climate change into building design strategies.* Through the consideration of this interaction in an early stage of the design process, it will be possible to avoid (or at least reduce) the occurrence of negative impacts on energy usage and reach energy targets.

1.3 Uncertainties Related to Energy Simulation

The complex relationship that tightly ties climate conditions and dwellings makes necessary the use of building simulation techniques coupled with forecast weather data. One of the outputs of building simulation tools is the energy performance related to a particular external climate (Macdonald 2002). The calculation of these quantities is very important during the design process of buildings to understand which solution is better for achieving policy-based goals on energy. The construction industry, policy makers and people in general need to have reliable data showing how climate change is going to influence the future thermal performance of buildings. Only with certain results will it be possible to choose the best measures. For example, whether is better to install external shading or to increase the thermal mass of the building with the use of PCM (P. d. Wilde et al. 2008), or if external insulation performs better than internal insulation. In addition, energy consumption predictions are very important for policy-making. Unfortunately, predictions of building performances in future climate are plagued with uncertainties, causing difficulties for planners taking decisions. These uncertainties rise from different factors, which according to de Wilde et al. (2008) can be categorized in three categories. The first type of uncertainties is related to the building itself: in the future dwellings could be different compared to how they currently are, following upgrades and replacements of their systems and components. Besides this, the computer model of the building represents reality only to a certain extent and so there are uncertainties in the resolution of the model and in the assumptions regarding the modelling and the simulations such as material properties, coefficients and the choice of algorithms for the simulation (Macdonald 2002). The second category concerns the operation of the dwelling and includes how changes in appliances and occupant behaviours can influence the results. The third category is about climate change. Firstly, the production of carbon dioxide and other greenhouse gases will continue to change atmospheric composition but there is less confidence regarding the degree of change. Climate is changing in response to human perturbations and many other variables that are almost impossible to predict with precision. Secondly, there are many uncertainties regarding the generation of future weather files. Climate models and future scenarios, used in this process, are just approximations of reality and cover a portion of the unknown, and probably larger, range of possible future climates. Moreover, the algorithms used for their generation are too simple because they do not consider all the dynamic interaction between different variables. According to Zichichi (Sacchi 2012), in fact, it is not possible to calculate future weather data on the basis of linear mathematical equations as researchers do now, because of the complexity of the phenomenon itself. Finally, uncertainties in the prediction of climate increase if the model is used at a regional level because the prediction of local environmental effects is more difficult compared to a global scale (Schiermeier 2010). While uncertainties regarding building modelling and operation could be reduced with accurate modelling or at least quantified, climate change uncertainties are almost impossible to eliminate. Uncertainties regarding how the climate might actually develop over the next decades and regarding its interaction with the building system will always be present in building simulation. Consequently, does not seem reasonable to generate reliable energy results from just one weather file and so only one possible future climate.

1.4 Robust Solutions to Climate Change

Given the fact that we cannot predict the future, we should seek strategies that are robust against a wide range of plausible future climates.

In statistics, the ability of a certain technique to deliver accurate results, although its assumptions are violated, is called the robustness of that technique. In other words, a robust statistics is resistant to errors in the results, produced by deviations from assumptions (Huber 1981). Analogously, the robustness of a building can be defined as the ability of the building to behave predictably under changing circumstances.

According to van den Ham et al. (2007) robustness is defined as

> the degree to which the building meets the design objectives with regard to the quality of the indoor environment and energy consumption when being used by its occupants in everyday (and varying) conditions.

Van den Ham et al. (2007), in their paper, highlight the need to make concrete and quantifiable the concept of “robustness”. Only in this way could it be useful in the design process and could lead to important energy saving in the future (van den Ham et al. 2007). Clearly, robust solutions are desirable, but the problem is how to find and assess them.

In this study, we will describe a methodology to identify robust refurbishment solutions that remain effective under the widest range of climate uncertainty.

Chapter 2

Sustainable Home Refurbishment

Sustainable development is

> development that meets the needs of the present without compromising the ability of future generations to meet their own needs (World Commission On Environment & Development 1987).

Referring to this principle and to the need to reduce greenhouse gases and fossil fuel consumption, the refurbishment of existing buildings constitutes a necessary action. As mentioned in the previous chapter, more than 40% of total greenhouse gas emissions and almost 30% of total energy consumption in European countries are produced by buildings in use or under construction. A growing population, increasing demand for building services and occupants' comfort, together with the rise in time spent inside buildings, will lead to increasing energy consumptions in building (Perez Lombard et al. 2008). High energy consumption are linked to inefficient construction and the extensive use of HVAC systems to provide for occupants' thermal comfort. As a consequence, upgrading existing, old and obsolete buildings to meet principles of bioclimatic design is one of the most cost-effective way to reduce energy consumption in industrialized countries (Smith 2001).

2.1 The Existing Housing Stock in Europe

Knowing the composition of the existing building stock is fundamental to understand the impact of refurbishment measures in terms of energy consumption. Focusing on Europe, the existing housing stock accounts for almost 196 million dwellings (Norris and Shiels 2004), with almost 50% of the existing residential buildings built before 1970, especially during the postwar economic boom between 1945 and 1970. In figure 2.1 the annual rate of construction of new dwellings is expressed as a percentage of the size of existing stock, showing some differences between countries but a similar trend throughout years. In particular, in terms of the average age of dwellings the Italian,

Year of construction	Greece	Spain	Italy	France	United Kingdom	Denmark	Sweden
<1919	3.1	8.9	14.2	17.0	17.0	19.7	12.1
1919-1945	7.2	4.2	9.9	13.2	17.0	16.1	14.7
1946-1970	31.8	33.5	36.8	17.4	21.0	26.4	37.0
1971-1980	24.5	24.1	18.8	25.2	21.8	16.6	16.8
1981-1990	19.1	13.6	12.2	10.2	20.0	9.1	9.4
1991-2000	14.4	15.7	7.9	8.5	na	5.4	5.5
>2000	na	-	-	8.4	na	6.7	4.6

Table 2.1: Percentage of dwelling' year of construction in Europe (Ministry of Infrastructure of the Italian Republic 2010).

English, Danish and Swedish housing stocks are relatively old compared to the other three countries, because only 20% of their dwellings were constructed after 1981. In France and Spain almost 30% of the houses were built in the same period, reaching the peak of 34% in Greece. The EU-Countries shown in the figure are the ones to which we will refer in the next chapters. Focusing on the type of building, on the bases of EUROSTAT information over half of the residential buildings in Europe are single family houses (53%), while the share of multi-family buildings is 37% and the share of high-rise buildings is 10% (calculated by the number of dwellings).

An important conclusion of this brief analysis is that about 70% of the residential buildings are over 30 years old and about 40% are more than 50 years old. Beside the fact that the life span of buildings is between 50 and 100 years, during which they need maintenance at many levels, it must be notice that most national building regulations regarding energy consumption were introduced just after the 1970s. In those years the major industrial countries faced an energy crisis, due to a shortage of petroleum, which led to energy efficiency measures such as thermal insulation of building envelopes in the building sector (Poel et al. 2007). As a result, almost half of the dwellings already existing in Europe perform poorly and have high energy consumptions due to their inefficient construction systems. Demolishing the obsolete buildings may seem the easiest and quickest way of improving the overall energy performance of the building stock and reaching energy targets. However, demolition is slow, costly and unpopular (Power 2008). For this reason the interest is shifting towards renovation, refurbishment and adaptation of the building stock (Kohler and Hassler 2002). The goal is to reach a performance level at least as good as newly built homes.

The next chapters will focus on the countries mentioned before and to a single family house constructed before energy regulations (i.e. pre 1970s).

2.2 Refurbishment Definition

Before going any further, it is necessary to lay down some important definitions to avoid confusion. Sometimes renovation, refurbishment, maintenance, conversion, restoration and modernisation are used interchangeably for indicating modifications in existing building. There are several reasons why the differences between these terms are so vague. Firstly, the degree of change to which each word refers is not clear (from minor repairs and substitutions to major interventions). Secondly, each intervention has a particular reason for which it is carried out (technical, aesthetic, functional, operational). Finally, there has always been an improper and imprecise use of these words in association with the correct measure (Giebeler 2009). According to Giebeler (2009), these are the definitions of the aforementioned terms:

> Renovation: it does not add anything new to the building stock nor does it replace old with new. Instead it maintains the value and the function of the existing building.
>
> Maintenance: it is limited to the replacement or repair of defective building components. Maintenance work is necessary at regular intervals between the total refurbishment intervals and is usually the responsibility of the building manager, not requiring any assistance from the design team.
>
> Conversion: it always affects the structure of a building. It extends the concept of refurbishment to interventions in the load-bearing members and/or the interior layout.
>
> Refurbishment: it includes intact, but, for example, outdated components or surfaces. The difference between refurbishment and conversion, however, is that refurbishment does not involve any major changes to the load bearing structure or interior layout.

The extent of refurbishment can vary (Giebeler 2009):

- Partial refurbishment: it refers to the refurbishment of one component or part of the building, which is directly interconnected with it, e.g. the façade, the ground floor or the east wing.
- Normal refurbishment: it involves an entire building or a clearly separate part of it. Demolition work is actually needed but it is usually kept to surfaces or preparatory work for upgrading fire protection, noise control or thermal performance. As far as the infrastructure is concerned, additions and changes usually take place but not up to complete replacement.

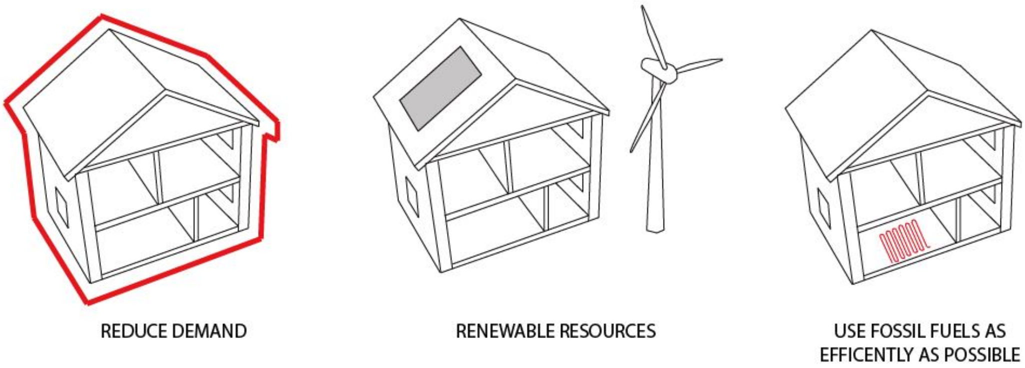


Figure 2.1: Trias Energetica measures.

- Total refurbishment: it involves extensive demolition measures, till the building is stripped and reaches its load-bearing framework, which remains unchanged, generally. To give some examples, total refurbishment would include complete replacement of infrastructure and building components according to the latest legislation.

2.3 Toward Sustainable Dwellings' Refurbishment

As stated in the previous chapters, intervention in the existing building stock can reduce energy consumption and therefore contribute to the reduction of greenhouse gases. According to many studies, these are just two of the many benefits of refurbishment (Papadopoulos et al. 2002; Gorgolewski 1995; Hong et al. 2006). The other advantages include improvements of the noise insulation, prolongation of buildings' life cycle, reduction of the negative impact on the environment, improvement of indoor thermal comfort conditions and a general increase in the buildings' value. Refurbishment, therefore, can be considered sustainable under many aspects. The "Green refurbishment" takes into account the whole building, in a way that the impact of the dwelling to the environment is minimized not only for today but also for tomorrow.

In this study we will focus on the benefits of refurbishment in terms of energy consumption and its strong relationship with climate change.

According to the "Trias Energetica", a model developed by the Delft University of Technology, there are three ways to pursue energy sustainability in the building sector:

- Reduce energy consumption (cf. Figure 2.1): it can be achieved by many means. Some examples are, using well insulated and air tight envelopes, applying efficient heat recovery of ventilation air during heating season, applying energy efficient

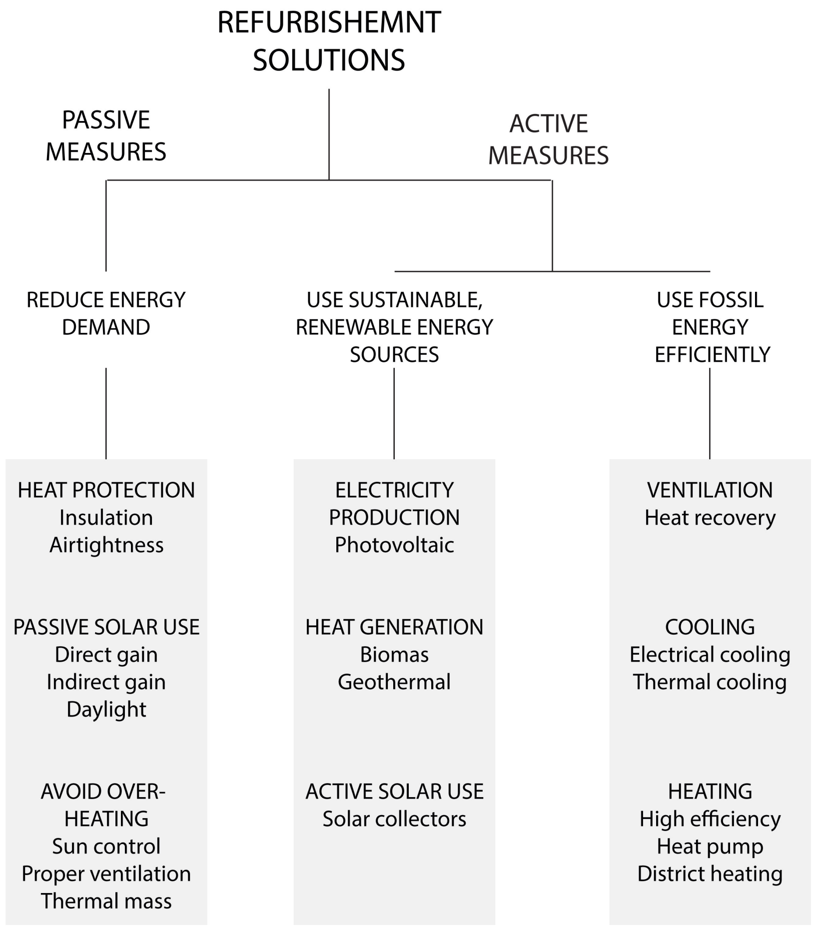


Figure 2.2: Active and passive measures in building refurbishment.

electric lighting and equipment and ensuring low pressure drops in ventilation air paths(Cauberg-Huygen Consulting Engineers and Per Heiselberg 2008). More details on this point are in the next chapter.

- Use sustainable energy sources as widely as possible (cf. Figure 2.1): it can be achieved by providing optimal use of passive solar heating, day lighting, natural ventilation, night cooling, earth coupling, apply solar collectors, solar cells, geothermal energy, ground water storage and biomass. The use of renewable energy must be optimized by the application of low exergy systems (Cauberg-Huygen Consulting Engineers and Per Heiselberg 2008).

- Use fossil fuels as efficiently as possible (cf. Figure 2.1): it means to use the least polluting fuels in an efficient way, e.g. heat pumps, high-efficient gas fired boilers, gas fired CHP-units (Cauberg-Huygen Consulting Engineers and Per Heiselberg 2008).

These three sustainable measures can be summarized in two categories: passive and active measures (cf. Figure 2.2). The first one refers to the reduction of the energy consumption, whereas the second one addresses the remaining energy consumption in an efficient way. In the following subsections an overview of all the solutions in the two different categories will be given.

2.3.1 Passive Measures: minimise energy consumption

Passive measures maximise the use of natural sources of heating, cooling and ventilation to create comfortable conditions inside buildings and reduce energy usage for the use of HVAC. They exploit environmental conditions such as solar radiation, cool night air and air pressure differences to modify the internal environment and provide comfort to the occupants. There are many passive measures that can be used for new dwellings such as building orientation, compact shape and the position and size of the openings, but these cannot always be modified in a refurbishment. Even in existing buildings there are many possibilities to reduce energy usage. These measures can be divided in three categories: heat protection, passive solar exploitation and overheating reduction. The first category includes all kind of insulation and airtightness solutions, which protect from the cold winter and the hot summer. The second category encompasses the exploitation of indirect and direct heat gains. Finally, the third category consists of shading systems, proper ventilation and use of thermal mass.

2.3.2 Active Measures: cover remaining consumption efficiently

Active measures differ from the passive ones because they make use of active building services systems to create comfortable conditions. These include devices such as boilers and chillers, mechanical ventilation and electric lighting. They also refer to the use of renewable energy sources such as PV, solar collectors, biomass, geothermal energy. If the energy produced by these means is not sufficient for the operation of the building, active measures envisage the improvement of heating, cooling and ventilation systems, for example with the use of heat pumps, heat recovery and the use of more efficient systems.

2.4 Passive Energy-Efficiency Strategies

This study will focus on passive measures related to the building envelope. The building envelope is a term used to describe the roof, walls, windows, floors and internal walls of a home. In particular, we will be looking at:

- insulation
- shading

- thermal mass
- airtightness.

All of these four categories deal with heat flow in different ways.

Heat flow is a phenomenon that conveys thermal energy from one location to another. The specific mechanisms are convection, radiation, and conduction. Convection involves movement of a heated fluid, such as air. The degree to which heat is transferred depends on the speed of the transport medium (air or wind speed, in the built environment) and the difference in temperature between the object and the fluid that is flowing past. Radiation refers to the transmission of energy as electromagnetic radiation from a body to another one. The heat emanated depends on the emission coefficient of the surface of the material and on its temperature. Conduction involves transfer of energy between adjacent molecules, which happens due to a difference in temperature. The heat conduction coefficient (λ) shows how much heat is transferred from a layer to another layer of material 1 metre thick and with a surface area of 1 m^2, and when the difference of temperature is 1 K (1°C). Each material has its own conduction capacity and therefore its heat coefficient. The greater λ is, the better the material can conduct heat. Another property of materials is heat resistance, which can be found by multiplying the reciprocal of the heat coefficient $\frac{1}{\lambda}$ by the thickness of the material d.

$$R = \frac{1}{\lambda}\ d \quad \left[m^2 \frac{K}{W}\right] \tag{2.1}$$

The heat transported via conduction is expressed with this formula (a modified form of Fourier's laws of heat transfer):

$$q = \frac{1}{R}\ (T_1 - T_2) \quad \left[\frac{W}{m^2}\right] \tag{2.2}$$

where $(T_1 - T_2)$ is the difference in temperature (ΔT) between two elements. This means that the greater the difference in temperature (ΔT), the greater the heat flow conduction (q). On the contrary, the greater the heat resistance (r), the smaller the heat flow conduction (q) (Gaalen and Linden 2013).

Let us first look at insulation, which is related to heat conduction. Installing insulation in the envelope is a fundamental energy-efficiency measure because it reduces heat flows from the inside to the outside in winter and vice versa in summer (Giebeler 2009). Uncontrolled heat flows and infiltration through the building envelope are the principal causes of high energy consumption, both in summer and winter. Figure 2.3 shows the percentage of heat losses in winter and figure 2.4 the heat gains in summer. According to Douglas in an uninsulated dwelling 25% of the heat escapes through the roof, 35% through the walls, 15% through the ground floor, 10% through the windows and 15% in air leakage through doors and holes in general (Douglas 2006). Different percentages of heat enter in the building during the hot season causing overheating and

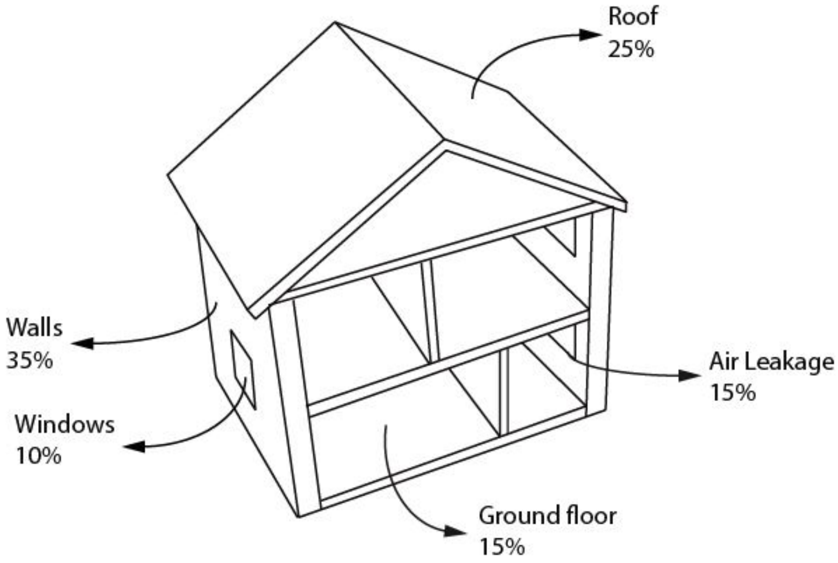


Figure 2.3: Percentage of heat losses in winter.

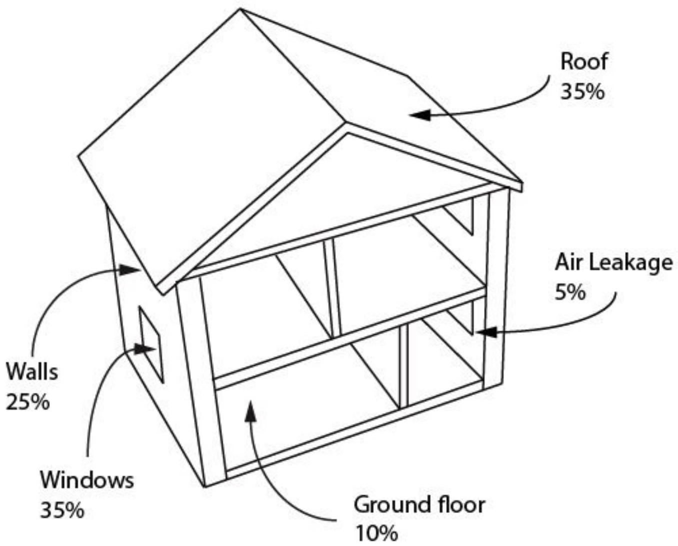


Figure 2.4: Percentage of heat gains in summer.

higher energy consumption for cooling: 35% through the roof, 25% through the walls, 10% through the ground floor, 35% through the windows and 5% in air leakage through doors and holes in general (Australian Greenhouse Office 2010). These percentages show how heat flow control throughout windows in summer become essential to achieving energy saving targets.

The building envelope consists of many layers of materials, each with different heat resistances. In order to calculate the energy need in a building, it is necessary to know the heat flows conducted through its envelope. The following formula is used:

$$Q = U \ A \ \Delta T \quad \left[\frac{W}{m^2}\right] \tag{2.3}$$

where

$$U = \frac{1}{R_T} \quad \left[\frac{W}{m^2 K}\right] \tag{2.4}$$

is the U value. R_T represents the sum of all the resistances of the materials and the inner and outer transfer resistances of the air. A is the surface area thought which the heat flows (Gaalen and Linden 2013). The U value is therefore the parameter used to describe the thermal performance of an envelope. We will refer to it in order to distinguish different refurbishment solutions for the building envelope insulation.

The reduction of heat thought shading systems is another measure for energy saving in building. The physical phenomenon involved in this case is the heat thermal radiation. Shading of the building and outdoor spaces reduces the occurrence of uncomfortably high temperatures, improves comfort and saves energy. The shading of windows to reduce unwanted heat gain is critical because unprotected glass is often the greatest source of unwanted heat gain in a home.

A passive solution that also contributes to energy reduction is the exploitation of the structure's thermal mass. In this case the physical phenomena that are involved are conduction and radiation. By alternately storing and releasing heat, high thermal mass stabilizes the extremes in daily temperatures. Large diurnal oscillations of the external temperature are minimized by heat accumulation and radiation (cf. Figure 2.5). In hot climates where there is significant temperature variation between day and night, heat can be absorbed during the day and then released in the evening. Heavy and dense wall materials, in fact, absorb heat and slow down its transfer through the wall. This moderates temperature changes, slowing down heat gain in summer, and storing heat in winter. In this way, thanks to the heat accumulation and radiation, a building with high thermal mass remains relatively cool by day and by night during the summer, and stays warm during the winter without loosing too much heat to the outside. A light mass building, instead, gets very warm in the daytime and cold at night in summer, and release the heat very quickly during the winter (Gaalen and Linden 2013).

The last measure that we are going to analyse is the reduction of unwanted draughts or air infiltration and leakage in a building. Reducing unwanted infiltration is one of

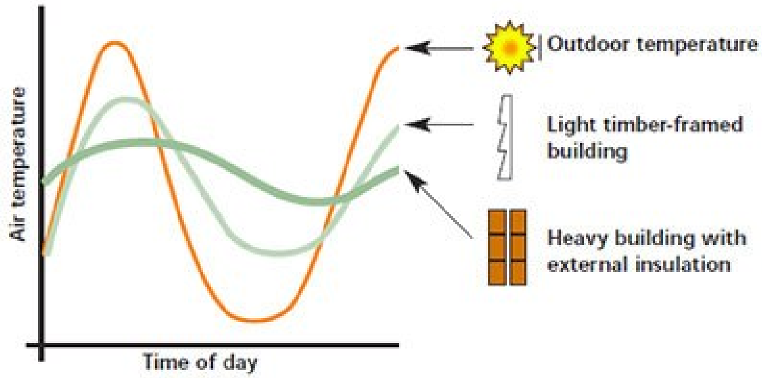


Figure 2.5: Thermal mass effect on temperature fluctuations (Australian Greenhouse Office 2010).

the easiest way to achieve energy reduction. In a typical house with no special attention to air sealing, air leakage accounts for about $\frac{1}{3}$ of the heating and cooling costs (Thorpe 2010). If a house is well insulated, the percentage of heat loss from leakage could be higher. building tight, i.e. paying attention to leakage, prevent conditioned air from escaping the building envelope and un-conditioned (hot or cold) air from entering the building envelope. The drawbacks of this strategy are less circulation, stale air and an increase in pollutants in the house. These pollutants can include carbon dioxide, smoke from cooking, volatile organic compounds (VOCs) from cleaning materials and furnishings, moisture, and other harmful chemicals (Gaalen and Linden 2013). That is the reason why a tight house must also be correctly ventilated, in a mechanical or natural way. Air changes are best controlled and regulated by a building' s occupants. This allows occupants to control humidity, cleanliness and temperature of the air to satisfy the interior comfort. In this study we will focus on the energy consumption due to infiltration, without considering the related problems of air quality and ventilation.

In conclusion, it can be argued that there are several measures to reduce energy consumption that can be applied in a refurbishment. All these measures plus the appropriate heating, cooling and ventilation systems should be coordinated with each other in order to provide good thermal comfort inside and save energy. Only then can refurbishment work be successful over the long-term.

In the following subsections the main passive solutions will be presented in detail. The envelope insulation will be described referring to each part of the building (walls, roof, floors and windows), whereas the other three measures will be illustrated referring to the whole dwelling.

Insulation materials	U-value ($\frac{W}{mK}$)
Aerogel	0.013-0.018
Phenolic foam	0.022
Polyurethane	0.023
Mineral wool	0.035
Expanded Polystyrene	0.038
Cellulose fibre	0.040
Wood fibre	0.044
Sheep's wool	0.04-0.057

Table 2.2: Thermal conductivity of common insulation materials (Burton 2011).

2.4.1 Insulating walls

Insulation acts as a barrier to heat flow and is essential to keep buildings warm in winter and cool in summer. There is a wide variety of insulation materials. The first parameter used to distinguish them is their thermal performance, represented here by their U-value. There are many other factors that can influence the choice of a material over another. These factors include embodied energy, suitability in the building, ease of installation, environment impact, fire resistance, durability and, of course, cost (Burton 2011). In this study we will focus on the thermal performance of the materials, leaving aside the other parameters. Table 2.2 shows the U-value of common generic insulation materials used in houses. In this list Aerogel is the "best" material because its thermal conductivity (U-value) is the lowest.

In the case of uninsulated dwellings, insulation can be added to them with varying effectiveness depending on the construction type and where the insulation is placed. If a building has cavity walls, the first choice is to fill the cavity with insulation (cf. Figure 2.6). The insulation, which is injected into the cavity via holes drilled through the outer leaf, can be selected from many kind of materials. The most common cavity-fill insulations are polystyrene beads and mineral fibres. This method allows to greatly reduce the U-value of a standard cavity wall without affecting the existing exterior or interior surface, and with minimal disruption. Depending on the dimension of the cavity and on the type of insulation, cavity wall insulation may not be enough. If this occurs there are other insulating solutions that can also be applied to solid walls.

The first measure is external insulation. It has the advantages of less disruption inside the house, retaining thermal mass inside, eliminating cold bridges and providing a weather-proof barrier. It has some disadvantages such as the need to extend the roof and openings sills and the necessity to move drainage pipes. Moreover it changes the external appearance of the building, a fact that can be positive if the existing finish of

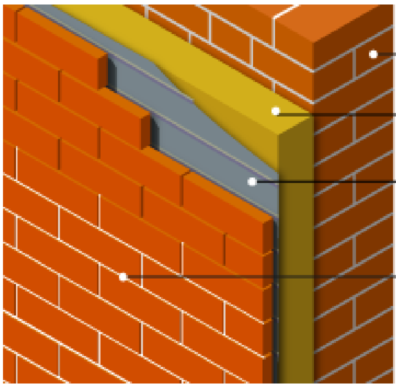


Figure 2.6: Cavity wall insulation (Source: www.greenspec.co.uk/building-design).

the building is poor, or negative if the building has good architectural features. This last factor can be crucial in the decision whether or not to opt for external insulation. In fact, if the external walls are uninteresting. As they are affected by dampness and present cracks or other problems, the externally applied insulation may be the ideal solution. In one operation, it improves thermal performances, appearance and protection from the external weather. There are two ways to insulate the building from the outside:

- Wet render system: It consists of insulant, adhesive mortar and/or mechanical fixings, profiles and edgings used on corners and on windows reveals, a base coat render incorporating a glass fibre or plastic or metal mesh and a top coat render with or without a finish. It is the cheapest method among external insulation (cf. Figure 2.7).

- Dry cladding system: it differs from the previous system because the insulation is fixed to the external wall in particular points instead of all the surface. It consists of: insulant, a supporting framework or cladding fixing system connected to the wall, a ventilated cavity, cladding materials and fixings (timber panels, stone or clay tiles, brick lips)(cf. Figure 2.8).

The second type of measure that can be applied both to cavity and solid walls is the internal insulation. It has the advantages of not changing external appearance and of being less expensive compared to the external insulation. Moreover it is not affected by external weather and its application does not require scaffolding if the ceilings are not too high. However there are also some disadvantages. The first one is the reduction of the internal space, the second is the need to move power points, skirting boards, radiators and wall fittings, and another one is the difficulty of fixing heavy items to the wall afterwards. Other drawbacks are the interstitial condensations that can occur and the impossibility to eliminate structural cold bridging. There are three common systems of internal insulation:

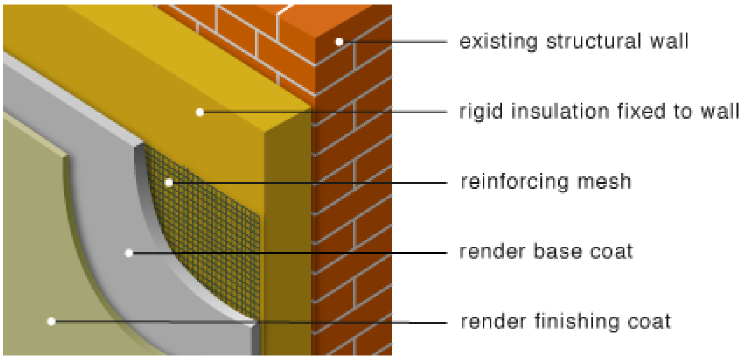


Figure 2.7: External wall insulation: typical wet render system applied to an existing solid masonry wall (Source: www.greenspec.co.uk/building-design).

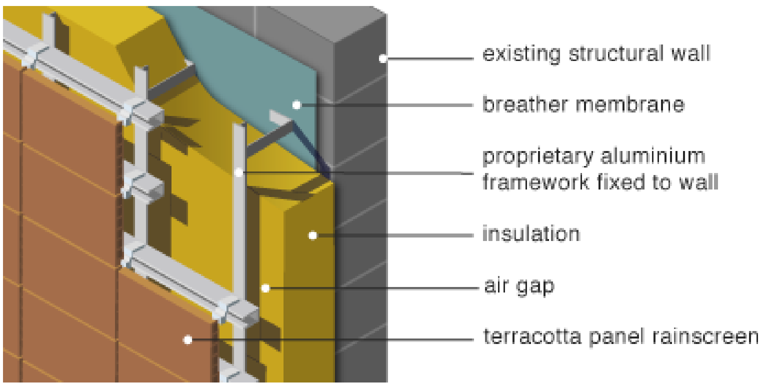


Figure 2.8: External wall insulation: typical dry cladding system applied to an existing solid masonry wall (Source: www.greenspec.co.uk/building-design).

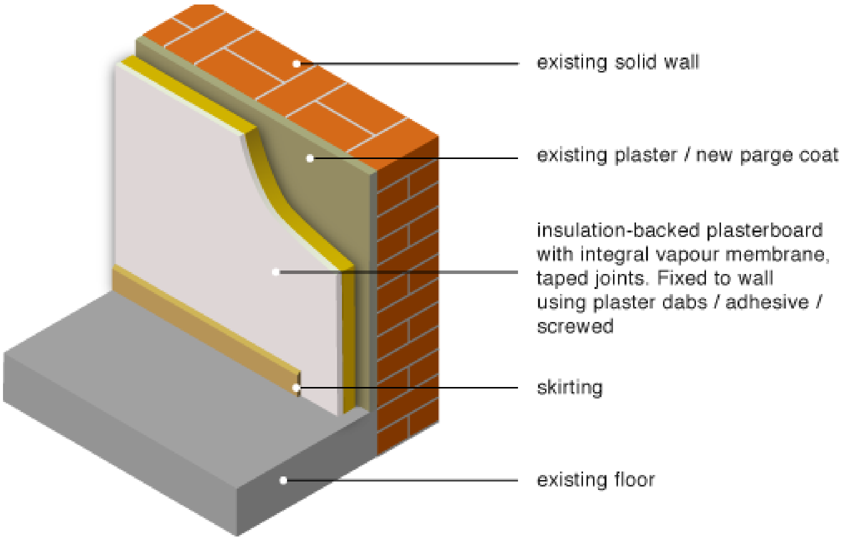


Figure 2.9: Internal wall insulation: insulated plasterboard (Source: www.greenspec.co.uk/building-design).

- Insulated plasterboard: thermal boards are glued directly on to the internal walls. Some of these boards have a built-in vapour control layer to stop moist internal air condensing on the cold wall behind the insulation. The internal wall must have an even surface. Airtightness must be preserved with continuous ridges of plaster adhesive round the edges of the wall and around all windows and doors. Between the board and the insulation there must be no gaps and between the insulation and the internal wall air movement must be avoided (cf. Figure 2.9).
- Insulation and battens: a rigid insulation must be fixed to the wall trough battens. It consists of vertical timber battens or metal furrings fixed to the wall, rigid or semi-rigid insulation boards between the battens and plasterboard. Also in this case a vapour check barrier is necessary between the insulation and the plasterboard (cf. Figure 2.10).
- Stud insulation: it should be employed on a wall that has previously suffered from damp. In this way it is possible to create a cavity gap between the internal wall surface and the insulation. This system is also good where the wall is bowed or uneven. It consists of: timber, extruded polystyrene or metal frame braced between the floor and ceiling, insulation stapled to the frame leaving a 30 mm air gap between insulation and wall, a damp-proof membrane between the studs and the wall and plasterboard. The number of studworks depends on the use of the dwelling. In some situation, in fact, for example in rented accommodation, a more robust structure is needed. Anyway, it must be kept in mind that more studwork will reduce thermal performances due to thermal bridges (cf. Figure 2.11).

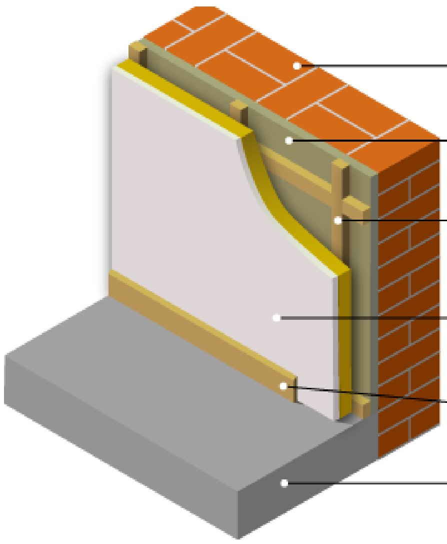


Figure 2.10: Internal wall insulation: battens with insulation (Source: www.greenspec.co.uk/building-design).

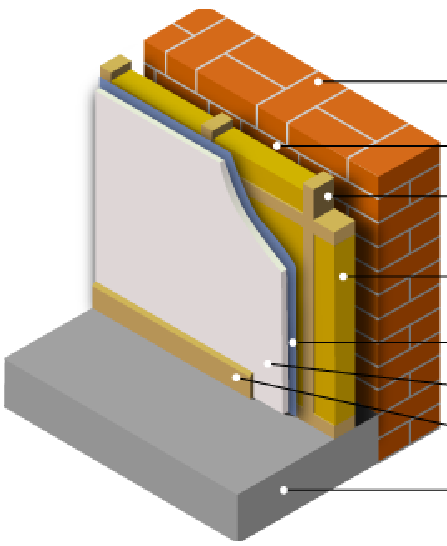


Figure 2.11: Internal wall insulation: stud insulation with air gap (Source: www.greenspec. co.uk/building-design).

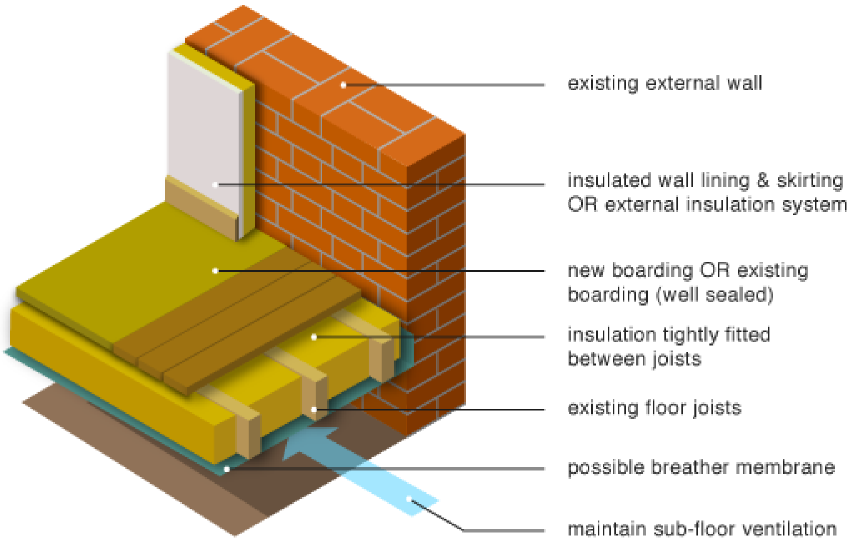


Figure 2.12: Timber ground floor insulation (Source: www.greenspec.co.uk/building-design).

In some cases, a combination of different refurbishment technologies may be justified. However, in most cases, the use of a single system is usually a better solution. Some possible combinations of the three solutions are cavity insulation combined with internal or external insulation and internal insulation combined with external insulation (Energy Saving trust 2006a, Highfield 2009; Burton 2011; Thorpe 2010).

2.4.2 Insulating ground and exposed floors

Underfloor insulation is one of the measures to consider in most existing houses to make them warmer, healthier and more comfortable. It is an intervention that in homes with accessible underfloor spaces is relatively cheap and easy to do. This kind of insulation is necessary in all the floors that separate the interior space from the external (ground floors, floors above garages, walkways and recesses). Various materials can be used in floor insulation, but much depends on the size, shape and type of floor and the conductivity of the ground below it. The principal difference is due to the type of floor.

- Suspended timber floor (cf. Figure 2.12): the two ways to insulate this kind of floor are from above and from below. The first method consists in lifting the existing floor-boards and, after fixing a net over the joist, putting insulation between them. After this operation it is necessary to replace the floor-boards and seal all the gaps between boards, skirting and service entry points. The method from below consists in fixing the insulation under the floor-boards and joists, after sealing all the joints between boards, below skirting and entrance service points. To conclude

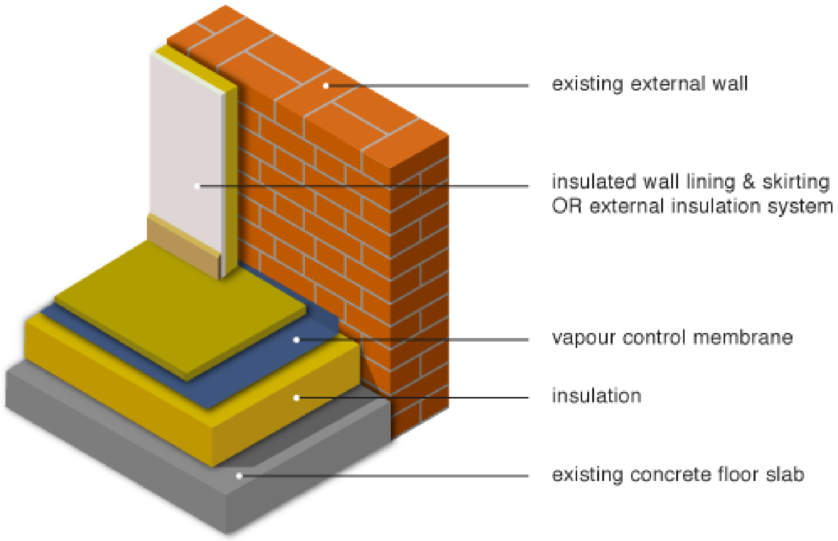


Figure 2.13: Concrete ground floor insulation (Source: www.greenspec.co.uk/building-design).

the operation it is necessary to fix a plasterboard to the underside of the floor, connecting it to the joists.

- Concrete slab (cf. Figure 2.13): if the building has solid concrete floors, the only way to insulate them is to install insulation from the above. This method consists in putting a rigid insulation on top of the concrete slab, follow by a vapour control layer, and then a floor finish. The drawback of this measure is that a higher floor, due to the thickness of insulation, is likely to cause problems at stairs and door thresholds. Moreover it is necessary to relocate skirting boards and electrical points (Energy Saving trust 2006a; Highfield 2009; Burton 2011; Thorpe 2010).

2.4.3 Insulating roofs and exposed ceilings

In addition to the possibility of defective and decaying materials, existing roofs are unlikely to meet with current energy regulations, even less with best practice standards of thermal performance and air permeability.For this reason roof insulation is an essential intervention for the reduction of energy consumption. Several techniques are available to use in the upgrading of roofs and the refurbishment can usually be carried out with the minimum of disruption of the building's structure. Roof insulation techniques differ depending on the type of roof, which can be pitched or flat. In the following list we will give a brief explanation of the more common roof insulation techniques according to the type of roof.

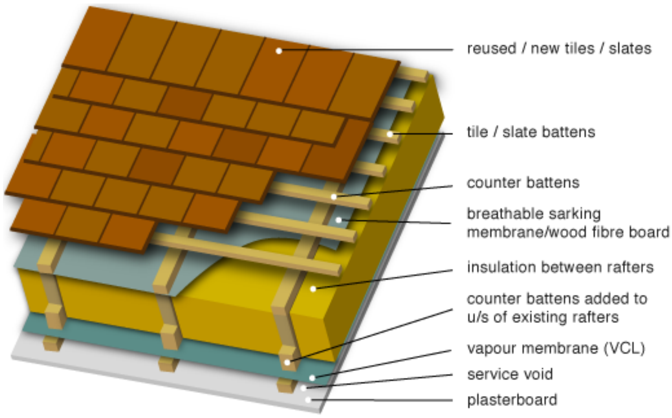


Figure 2.14: Insulation of the roof between and below rafters (Source: www.greenspec.co.uk/building-design).

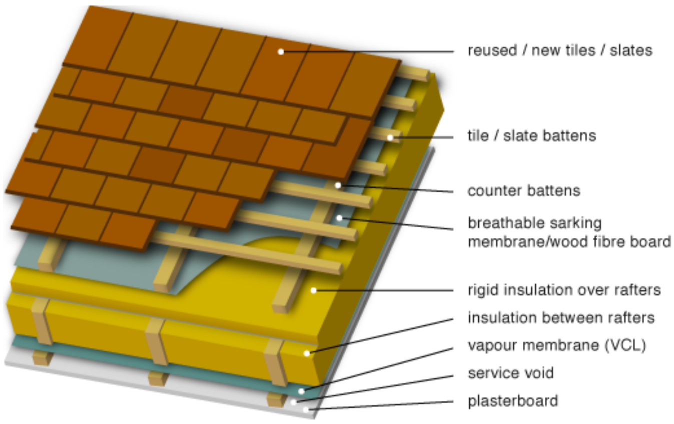


Figure 2.15: Insulation of the roof between and above rafters (Source: www.greenspec.co.uk/building-design).

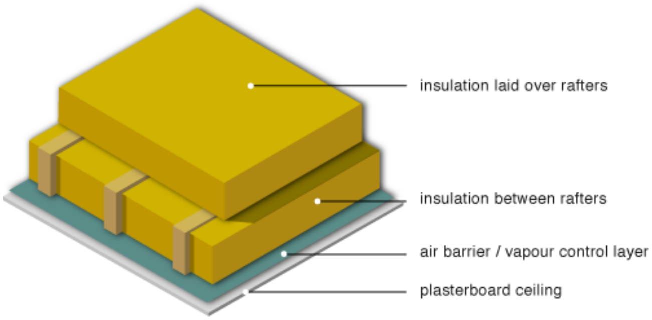


Figure 2.16: Loft insulation (Source: www.greenspec. co.uk/building-design).

- Pitched roof: a pitched roof can be upgraded by inserting an additional insulating layer, which can be either at ceiling level or at rafter level (below or above).

  – Internal roof insulation (cf. Figure 2.14): if the roof space needs to be used by the occupants, it is necessary to provide the new insulation at rafter level to make the space underneath the roof warmer. This is, indeed, the approach for attic rooms or loft conversions. In this case, insulation is fixed between and below the rafters. This operation is possible in buildings where no ceiling exists and when the accommodation extends into the roof space. The pros are the minimal raising of existing roof line and and the presence of an extra depth of insulation. The cons, however, are the reduction of internal space with a lost of head height within the room, and the presence of thermal bridging through the rafters. Insulation can also be placed just between the rafters to keep the internal height of the ceiling, but with a thinner layer of insulation thermal properties of the roof will be worse.
  – External roof insulation (cf. Figure 2.15): insulating between and above rafters must be done when the roof tiling is being replaced and renewed. It is necessary to raise the roof slightly but this solution maintains existing internal space and head heights. This kind of insulation is, in fact, the ideal solution where internal space is at a premium and where high thermal performance is needed. The latter can be achieved with extra depth of insulation between and above the rafters and the reduction of thermal bridging from rafters.
  – Loft insulation (cf. Figure 2.16): where a ceiling exists beneath the roof space and the roof space is not intended for use, the insulation can be inserted at ceiling level to reduce heat loss into the void above the space and into the exterior. Insulation at ceiling level consists of insulation between joists of the ceiling, additional insulation laid above joists, a vapour control layer under the insulation and a plasterboard ceiling. Any recessed lights within the ceiling below the insulation must be housed in airtight, fire-proof enclosures and not cause breaks in the vapour control layer and insulation.

- Flat Roof: The method used to upgrade the thermal performances of an existing flat roof depends to some extent on its construction. There are two main flat roof types, the timber flat roof and the concrete flat roof. In any case, the insulation can be placed in three different positions:

  – Warm roof (cf. Figure 2.17): the roof deck is kept warm through placing the insulation above it. The waterproof covering is above the insulation and the vapour control layer is placed below the insulation.
  – Inverted warm roof (cf. Figure 2.18): in this kind of roof the insulation is placed above an existing waterproofing membrane. The insulation effectively

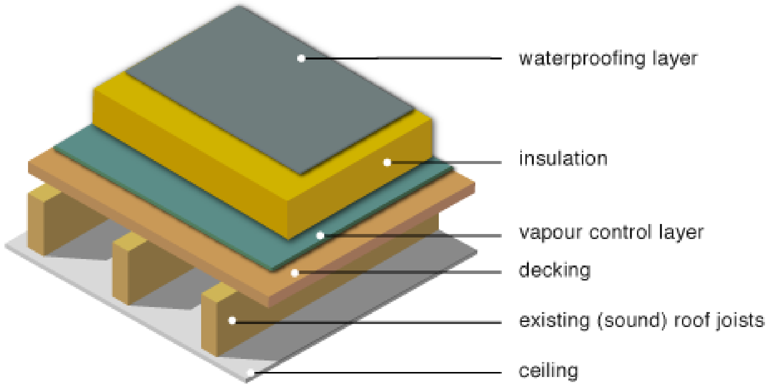


Figure 2.17: Warm roof insulation (Source: www.greenspec.co.uk/building-design).

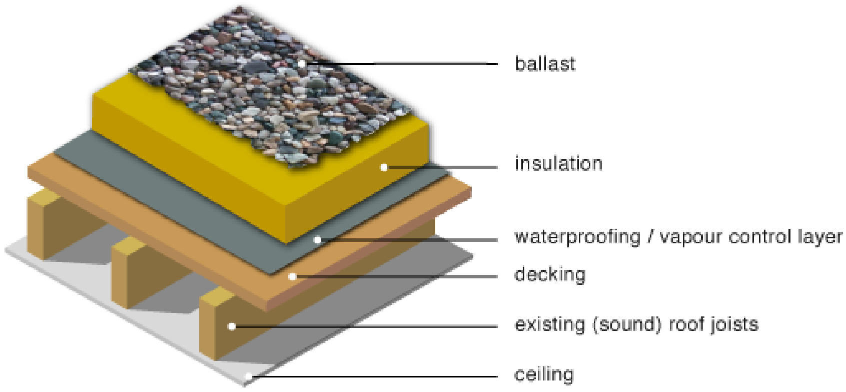


Figure 2.18: Inverted warm roof insulation(Source: www.greenspec.co.uk/building-design).

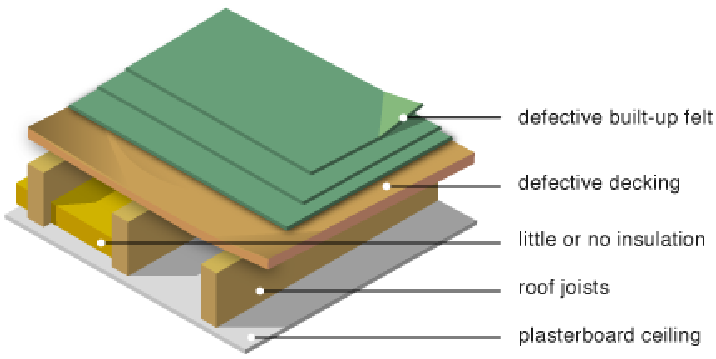


Figure 2.19: Cold roof insulation (Source: www.greenspec.co.uk/building-design).

"protects" the roof membrane from thermal stress, UV light and mechanical damage. The insulation layer is prevented from lifting by adding ballast above it. In this case the insulation must be of a type that is unaffected by moisture because rain will always penetrate the ballast and reach the insulation layer.

– Cold roof (cf. Figure 2.19): when it is not possible to construct a warm deck, internal insulation can be used. Any moist air penetrating the roof is dispersed through ventilation between the insulation and the underside of the deck and for this reason this system is susceptible to internal condensation on the cold deck surface. It then requires a highly effective internal vapour barrier, with complete sealing at wall junctions and around any service penetrations. In any case, upgrading methods that produce a "cold roof" must be avoided because this would involve providing adequate ventilation to remove moisture (Energy Saving trust 2006a, Highfield 2009, Burton 2011; Thorpe 2010).

2.4.4 Insulating windows

A typical house gains 35% of external heat in summer and loses 10% of its heat in winter through the windows. The solar heat entering the building through windows depends on the strength of the sun light, its angle, and the effectiveness of the glazing to transmit, absorb or reflect its energy.

Windows lose heat in winter through different phenomena (cf. Figure 2.20). The first and the most important one is radiation through the glazing, which is how around 2/3 of the heat flows out of the house. Convection occurs through air leakage around the frame and the opening sashes. Convection within the glazing cavity (if the window has double or triple glazing) is another mode of heat transfer, even though it is relatively unimportant. The last mode of heat transferring is conduction. Heat is conducted through the window frame and the rate of conduction depends on the material of the frame. Conduction occurs in a small but not insignificant part also in double glazing windows through the aluminium spacer bars of the panes.

On the other hand, windows play an important role in energy gain. Figure 2.21 shows how windows gain heat trough glazing in two ways: solar gain directly transmitted (primary transmittance) through the glazing and energy absorbed by the glazing and subsequently transferred inwards by convection and radiation (secondary transmittance). The G-value of a glass pane measures the degree to which glazing transmits heat from sunlight. It represents the fraction of the heat from the sun that enters through a window and is expressed as a number between 0 and 1. The lower a glazing's G-value, the less solar heat it transmits. The US equivalent of G-value is the Solar Heat Gain Coefficient (SHGC), which differs from the European G-value in using a different value

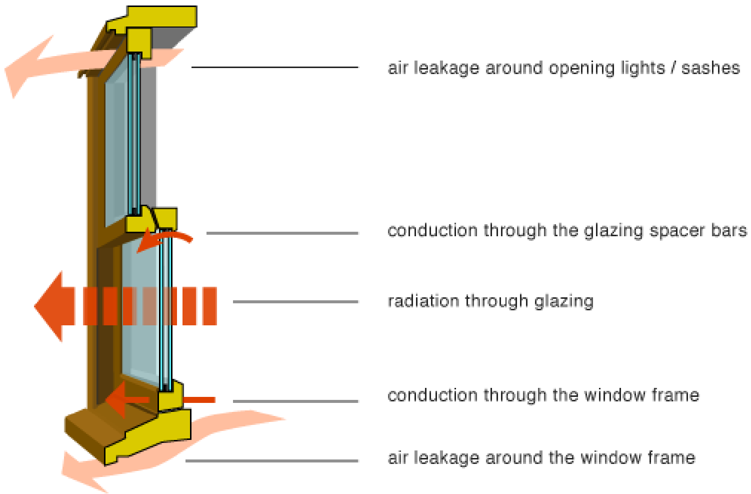


Figure 2.20: Heat losses through windows (Source: www.greenspec.co.uk/building-design).

for air mass (Energy Saving trust 2006b; Highfield 2009, Burton 2011; Thorpe 2010).

In conclusion, by substituting windows during a refurbishment it is possible to control solar gain by modifying the following variables:

- thickness of the panes
- number of panes: double or triple glazing
- coating on the glass (Low-E glass): by coating the face of the inner pane of glass with metal or metal oxide, short wave radiation from the sun is permitted to enter the building, whilst long wave radiation in the form of heat from the inside is reflected back into the room. In summer the coatings can contribute to the risk of overheating by slightly reducing the amount of short wave radiation transmitted through the glass (cf. Figure 2.22).
- cavity size
- cavity fill: filling the gap between the glass panes with a gas that has low conductivity such as argon or krypton (as well as the more expensive xenon) at atmospheric pressure improves the window performance by reducing conductive and convective heat transfer. This is mostly used in conjunction with low-emissivity coatings.
- sealants (for gaps and leaks)
- frame materials.

This study will focus on the U-value of windows, without taking into account the other variables.

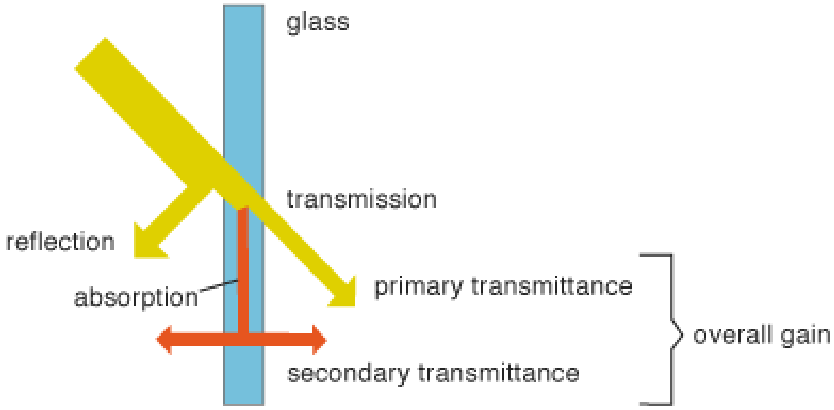


Figure 2.21: Solar gains trough windows (Source: www.greenspec.co.uk/building-design).

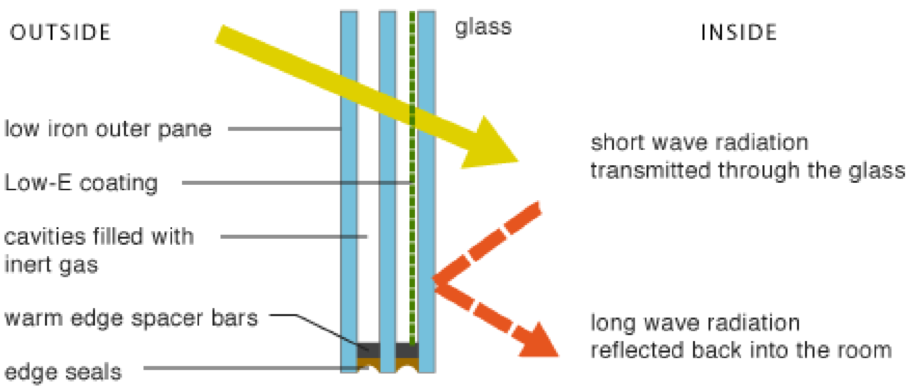


Figure 2.22: Low-E glazing (Source: www.greenspec.co.uk/building-design).

2.4.5 Avoiding overheating with shading systems

Strictly related to the thermal properties of windows and to heat flows through them are the shading systems. In order to avoid overheating in fact, it is necessary to install shading systems to all the openings, especially the ones that are South-oriented. The shadings can be shutters, blinds and curtains and they can be applied internally or externally. Interior shadings include: bifold interior insulation shutters and manual or motorized interior curtains. Exterior shadings include: shutters, roll-down shade screen and retractable awnings. It must be kept in mind that internal shadings can cause overheating inside the building. In fact, they absorb heat while screening the room from the solar rays and then release it through convection (Highfield 2009; Burton 2011; Thorpe 2010).

2.4.6 Use of thermal mass

Thermal mass describes a material's capacity to absorb, store and release heat. The physical principle is similar to a battery: the material "is charged with" heat to a certain limit as far as the ambient environment is is warm or there is a source of heat and then it discharges the heat as the adjoining air space becomes relatively cooler. Thermal mass dampens the amplitude of temperature fluctuation, and for this reason it works best where there are high differences in temperature over the course of a day. Where there is little normal variation in the ambient temperature, the case for thermal mass starts to become more marginal and complicated. For example, thermal mass works better where it is beneficial to absorb the excessive solar gain in the building fabric during daylight hours. The same heat is then released into a cooler night-time space.

In future scenarios that reflect a warming climate, housing can receive significant benefit through using thermal mass combined with shading and appropriate ventilation to mitigate the effect of summer time peak temperatures. Some researchers suggest that at higher latitudes the use of thermal mass could be counter productive (Tuohy et al. 2005). There are different materials that can be used in a house to increase its thermal storage capacity. Solid wood panels can be used to provide helpful degrees of thermal mass while limiting the amount of embodied energy found in masonry construction. Internal finishes including floors, ceilings and partition walls can provide sufficiently high thermal mass without resorting to masonry construction. Phase change materials (PCM's) are capable of storing a large amount of heat in a small volume, and do this without noticeably heating up or cooling down. In order to do this they use their latent heat capacity. Latent heat can be absorbed or released, for example, when a substance changes phase from solid to liquid form. (Meijs and Knaack 2009). Incorporating PCM into gypsum plasterboards is widely used in lightweight buildings. They can be placed on walls, floors and ceilings but also integrated in HVAC systems (Mehling and Cabeza 2008). The performance of a phase change material in buildings is dependent on a large number of variables. When selecting a PCM material to be incorporated in a building the material itself should ideally possess all of the following properties:

- Suitable melting temperature: it is logically the first criterion upon which a material is selected. The correct melting point depends on climatic conditions and the desired comfort temperature. For best performance use a material with a melting point approximately 3°C below maximum design temperature.
- High storage density: this is dependant on a material property called heat of fusion, i.e., the amount of heat needed to change the state of a substance from solid to liquid. Good heat transfer inside the PCM is also necessary, so it is able to take up and get rid of heat easily. A high thermal conductivity is thus a beneficial trait.
- Minimal volume change: when materials melt and solidify their volume changes as a result, but these changes must be kept minimal as typical building components and structures do not change in shape or size
- Cycling stability: usability must be guaranteed over a long material lifespan.
- Healthy material: for environmental and safety reasons the material should be non-toxic and non-flammable.
- Not costly: cost must be kept low so the final product can financially compete with other thermal storage solutions.

The most common PCM materials are paraffin wax, fatty acid and salt-hydrate, but none of them possess all the aforementioned properties for an ideal thermal storage solution (Mehling and Cabeza 2008, Baetens et al. 2010; Zhou et al. 2012).

2.4.7 Improving the airtightness of the structure

The airtightness of the building estimates how much air leaks in and out of the building. Air leakage is a major cause of energy loss, typically around 20% in older houses, from space heating. In modern houses, where heat loss is less through other means, air infiltration can account for up to a third of the total heat loss, leading to high energy consumption and uncomfortable indoor spaces (Shah 2012). Infiltration is due to uncontrolled air leakage in and out of a building which is not for the specific and planned purpose of exhausting stale air or bringing in fresh air. It can occur in many part of the building such as beneath doors and door frames, through windows, around window frames, through the eaves, and through many gaps and holes that are present in the building (Thorpe 2010). Airtightness is measured in air changes per hour (ACH), which is the number of times the air in a room is replaced by outside air in an hour. In an old and obsolete house, ACH ranges between one and two volumes per hour but

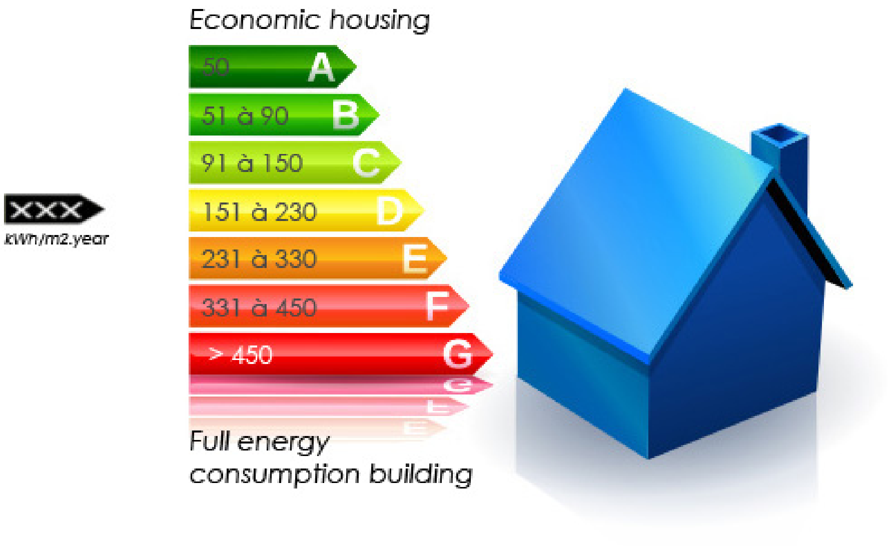


Figure 2.23: Classification of buildings depending on the level of annual consumption of primary energy in kWh per m^2 (Source: /www.concept-bio.eu/label-bbc-bbc-effinergie.php).

can be much higher. A refurbished and tight home can reach values of 0.6 and 0.5 ACH. Some simple measures can be taken to improve the airtightness of a building. Draught-proofing is one of the least costly, yet effective, measures to make efficient use of energy in dwellings. All gaps, holes and laps in membranes must be properly sealed together with the installation of a continuous airtight barrier. Having made the building airtight, mechanical ventilation is essential.

2.5 Drivers of Sustainable Refurbishment

Refurbishment of existing building is a key issue in European energy saving targets. For this reason many strategic documents have been published regarding energy use efficiency such as Green Book, Building Energy Efficiency Directive, Energy Efficiency Action Plans and European Energetic Tools establishment (Mickaityte et al. 2008). As well as reducing energy consumption, adopting passive design strategies can help building ratings across standards such as PassivHaus, BREEAM, The Code for Sustainable Homes, LEED and in general can lead to better results in Energy Performance Certificates (EPCs). The EPCs are documents that give a property an energy efficiency rating from A (most efficient) to G (least efficient), which all domestic and commercial buildings available to buy or rent must have (cf. Figure 2.23).

The European Parliament and the Council on energy efficiency of buildings in-

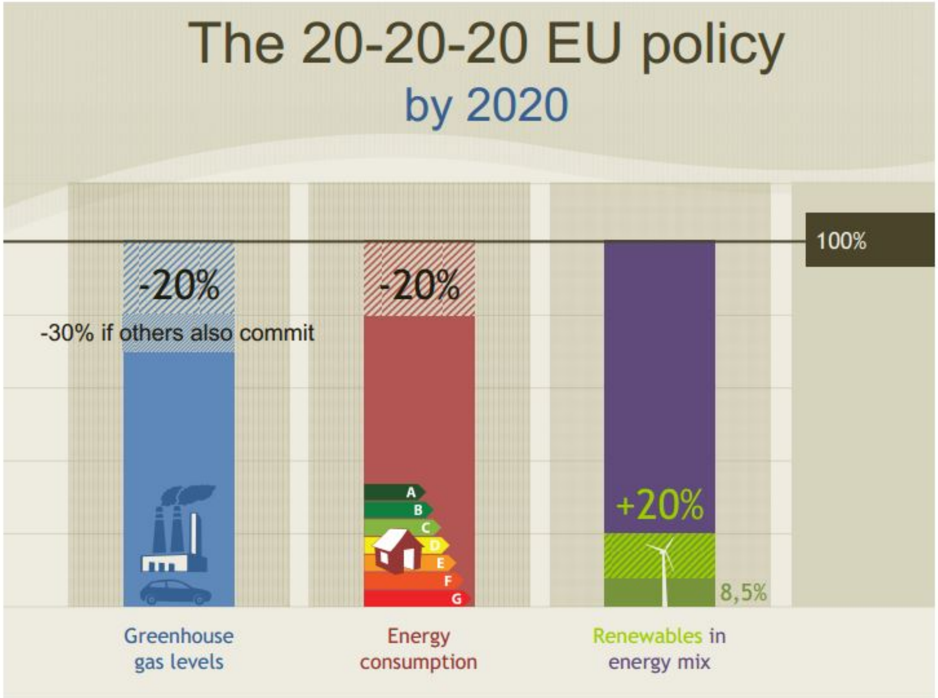


Figure 2.24: 20-20-20 EU Policy (Source: ec.europa.eu/energy/efficiency).

troduced EPCs in the European Directive (2002/91/EC) on the Energy Performance of Buildings (EPBD)(European Union 2002). The first aim of EPBD was to realise potential savings in the built environment mainly through improving energy efficiency, focusing on the building envelope and on the installed equipment such as heating, air-conditioning and ventilation. Member States were in charge of identify a methodology to calculate and rate the energy performance of buildings, set minimum energy performance standards for new and existing buildings, and establish the parameters of energy performance certificates.

In 2009 a major policy package was adopted and became a binding legislation known as the 20-20-20 EU policy. This climate and energy package includes the following targets for 2020 (cf. Figure 2.24):

- A 20% or more reduction in greenhouse gas emissions from 1990 levels.
- At least 20% of EU gross final energy consumption to come from renewable energy sources.
- At least 10% of transport final energy consumption to come from renewable energy sources.
- A 20% reduction in primary energy use compared with projected levels, to be achieved by improving energy efficiency.

In order to achieve the last point, the EPBD has been recast in 2010 (Directive 2010/31/EU), with the following changes (European Parliament, Council of the European Union 2010):

- Elimination of the 1000 m^2 threshold for existing buildings. There must be a minimum energy performance requirements for all existing buildings undergoing a major renovation .
- Decision to set minimum energy performance requirements for technical building systems (large ventilation, AC, heating, lighting, cooling, hot water) for new build and replacement.
- Decision to set minimum energy performance requirements for renovation of building elements (roof, wall, etc.) if technically, functionally and economically feasible.

EU member States introduced national laws, regulations and administrative provision to set energy performance certification for new and existing buildings that are subject to major renovations and to determine national Energy Performance (EP) numeric indicators (e.g., total energy use per building floor area).

Chapter 3

Case study

This study investigates the possible refurbishment interventions for a single family house of the period 1950-1970, focusing on energy usage for cooling and heating. The aim of this research is to discover in which way uncertainties over future changes in the European climate might affect the thermal performance of the existing housing stock. The starting point is a base case, which is then refurbished with the passive measures described in the previous chapter.

Figure 3.1 summarizes the topics chosen in the study. Climate change and refurbishment are, in fact, very broad subjects, which can be tackled in different ways. As previously described, we decided to deal with climate change adaptation and with passive refurbishment measures. In particular, figure 3.1 shows that we have chosen a sub-sample of common refurbishment options. The insulation has been developed in detail taking into consideration all of the parts of an envelope (walls, roof, floors and windows), whereas just two examples have been selected for the shading and one for each of the other two measures. The model of the base case is modified with just one passive measure at a time. In this way, our study is a one-at-a-time experiment, which does not take into account the combination of more than one solution. This is done to propose a simple framework for the basic understanding of the heat flow phenomena and thus the resulting energy consumption. To study the behaviour of a real refurbishment intervention in depth it will be necessary to include the combination of more passive measure to understand their interaction.

The goal of the research is to assess which refurbishment measure is robust to climate change and which one allows to save more energy compared to the base case. Building energy simulations are used to elaborate the data for each solution.

The following sections describe both the base case and refurbishment options in detail.

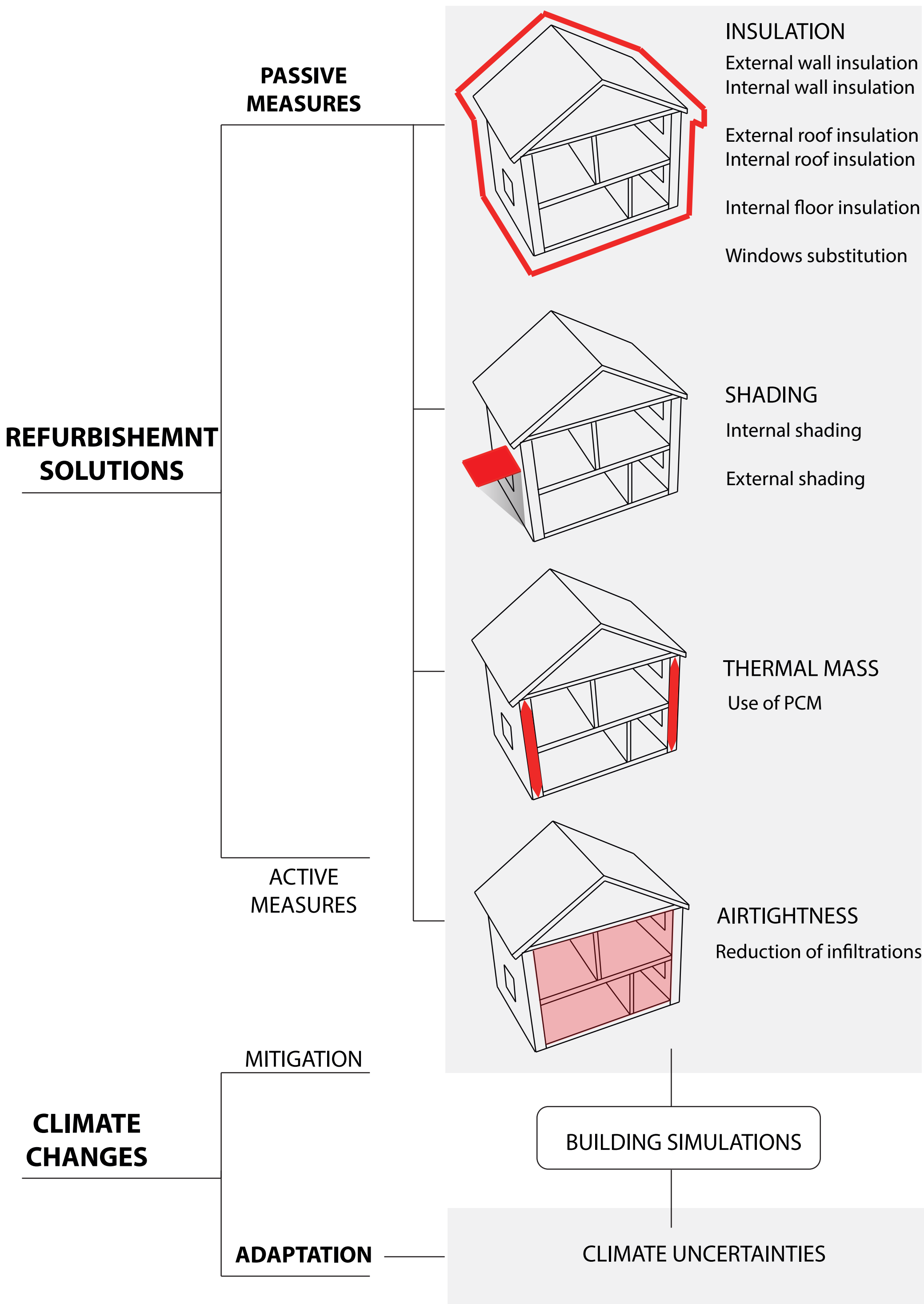


Figure 3.1: Summary of the choices made in the study .

Figure 3.2: The base case house modelled in DesignBuilder.

3.1 Base case

For our investigations, we modelled a single family home (cf. Figure 3.2). The program used for modelling is DesignBuilder, a graphical user interface for EnergyPlus [1].

The dwelling is composed of a ground floor, used during the day; an attic, used at night; and a cellar which is not regularly occupied. The ground floor has one living room and one kitchen facing south. Two bathrooms, two study rooms and the entrance face north. Three bedrooms and one bathroom around a central corridor compose the attic. In the cellar there are a laundry room, a multi-purpose space and three unheated zones.

The house is placed in an artificially empty urban setting without shading from other buildings, because the simulations will take place in different locations around Europe. In a real case, however, the surrounding environment must be known in detail. In fact, the shading of neighbour buildings and vegetation can have a crucial impact on the solar gain of the building and thus on its energy usage (Misni and Allan 2010).

3.1.1 Envelope construction

The house has been modelled according to typical European construction techniques used after the Second World War, before any national energy standards that dictated a minimum insulation level for a building (e.g. the Italian law n° 373 of 1976 “Norme per il contenimento del consumo energetico per usi termici negli edifici”). The dwelling uses a reinforced concrete structural frame (pillars and beams) and masonry block and

[1] a whole-building energy simulation program from the US Department of Energy (http://apps1.eere.energy.gov/buildings/energyplus)

Structure	Material	x (m)	c_p $(\frac{J}{kgK})$	λ $(\frac{W}{mK})$	ϱ $(\frac{kg}{m^3})$
Wall	Gypsum plasterboard	0.015	1000	0.25	900
	Masonry blocks	0.15	840	0.85	1650
	Air gap	0.05	-	R = 0.18	-
	Brickwork	0.12	800	0.84	1700
Roof	Gypsum plasterboard	0.015	1000	0.25	900
	Roofing felt	0.005	837	0.19	960
	Wood rafters	0.10	1420	0.15	600
	Clay tiles	0.025	800	1.0	2000
Ground floor	Ceramic floor tiles	0.03	850	0.8	1700
	Floor screed	0.07	840	0.41	1200
	Wood hardboard	0.05	2000	0.13	900
	Ventilated cavity	0.2	-	R = 0.09	-
	Cast concrete	0.10	1000	1.13	2000
Internal floor	Ceramic floor tiles	0.03	850	0.8	1700
	Concrete blocks	0.3	840	1.35	1220
	Gypsum plasterboard	0.015	1000	0.25	900
Internal partition	Gypsum plasterboard	0.015	1000	0.25	900
	Brick	0.12	840	0.72	1920
	Gypsum plasterboard	0.015	1000	0.25	900

Table 3.1: Base case envelope's materials and properties.

brickwork with internal cavity for walls. The ground floor is made of concrete, as are the internal floors, whereas the internal partitions are made of bricks. The pitched roof is composed of rafters and clay tiles. Because the building was constructed before the '70s, no insulation is present in the envelope.

Referring to the base case, the following U-values have been calculated:

- Walls: $U_w = 1.4\ \frac{W}{m^2K}$
- Roof: $U_r = 1.0\ \frac{W}{m^2K}$
- Ground floor: $U_g = 1.0\ \frac{W}{m^2K}$
- Internal floor: $U_f = 1.8\ \frac{W}{m^2K}$
- Internal partitions (not insulated): $U_p = 1.8\ \frac{W}{m^2K}$

Table 3.1 shows a more detailed description of the materials used, their properties and their thickness in the envelope.

Structure	Material	x (m)	λ ($\frac{W}{mK}$)	SHGC
Single glazing	Clear pane	0.006	0.9	0.81

Table 3.2: Base case windows' materials and properties.

Percentage	Orientation
8.98%	North
7.95%	East
19.61%	South
19.09%	West
2.09 %	Roof
13.87%	Total

Table 3.3: Window-to-wall percentages of the base case.

The airtightness of the building is considered very low due to the obsolete construction of the whole envelope. For this reason, in DesignBuilder the cracks template is set to be "very poor". In the program, the natural ventilation is set as "Calculated", the infiltration units are air changes per hour (ach) and the airtightness method is Crack template (Model Options/Data/Natural ventilation). This kind of setting for the ventilation implies that natural ventilation and infiltration air flow rates are calculated on the basis of the openings and of the crack sizes, buoyancy and wind pressure.

Regarding the windows, they have been modelled as single glazing. The pane chosen is a generic 6 mm thick clear glass with a U-value of 5.8 $\frac{W}{m^2K}$. In table 3.2 some properties are reported.

The aluminium frame construction of the windows has a thickness of 5 mm and a U-value equal to 5.8 $\frac{W}{m^2K}$. In DesignBuilder all the windows are modelled in the same way, with the same glass and frame. The only difference is in the percentage of openable glazing area which is equals to 10% for the roof glazing and to 20% for the other openings. The layout of the external windows is set at a preferred height of 1.5 m. No shading devices are modelled.

The window-to-wall ratios are shown in table 3.3. The majority of the openings are present in the south and in the west façade, whereas on the North and East façades, the percentages are less than half of the percentages on the South and West.

3.1.2 Activities

In DesignBuilder it is possible to set the activities inside the dwelling. In order to make the calculations easier, the internal gains (occupancy, lighting, computer and others) are lumped into a single value and timing schedule (Model Options/Gains Data:lumped). This option has been chosen because comfort calculations are not needed.

In the activity tab, the following boundary conditions and values have been set:

- Occupied floor area: 311.8 m^2;
- No holidays are taken into account;
- Design set-point air temperature equal to 26 °C for the air-conditioned building, which means that the cooling system is switched on when temperatures rise above 26° C;
- Design set-point air temperature equal to 20 °C for heating, which means that the heating system is switched on when temperatures fall under 20° C. The set back temperature is equal to 16° C;
- The internal heat gains are lumped in one number that includes all the different gains: heat gains from lights (2000 W), heat gains from machines (1000 W), heat gains from occupants (400) for a total of 10.9 $\frac{W}{m^2}$. The schedule is set to ON, so that the internal gains are constant all day/every day.
- The density is calculated considering 4 people living in the house, for a total of 0.0128 people/ m^2.

3.1.3 Building services

The building is equipped with mechanical heating and cooling systems in order to have inputs regarding heating and cooling demand. In Design Builder the HVAC properties are set as simple. In other words HVAC systems are modelled using Ideal Loads, and fuel consumption is calculated from loads using seasonal efficiencies. The HVAC sizing is set as "adequate". In this way heating and cooling equipment can always meet the demand and no autosizing is required. As for the mechanical ventilation the auxiliary energy consumption is set to 0 (no electricity consumption by fans and pumps). For this reason heating is not influencing the building's electricity consumption. In the "Calculation Options" tab the temperature control is set to "Air Temperature", both for cooling and for heating.

In the "HVAC Template" it is possible to set all the data referring to the mechanical system:

- Auxiliary energy ($\frac{kWh}{m^2}$) is equal to 0.00

Energy standard	Wall ($\frac{W}{m^2K}$)	Roof ($\frac{W}{m^2K}$)	Floor ($\frac{W}{m^2K}$)	Window ($\frac{W}{m^2K}$)
1st Level Italy	0.33	0.30	0.30	2.00
2nd Level Italy	0.25	0.23	0.23	1.70
PassiveHouse	< 0.15	< 0.15	< 0.15	< 0.80

Table 3.4: Thermal transmittance of the envelope for the Italian Energy standard and the PassiveHouse standard.

- "Compact Type" is set to CAV, for modeling constant volume system
- Natural Ventilation is set to "on" with a rate of 0.5 ac/h
- Mechanical Ventilation is set to "off"
- No Economizer and Heat Recovery are considered
- Heating system is set to "on" with a system CoP equal to 0.9
- Cooling system is set to "on" with a system CoP equal to 3.2

3.2 Refurbishemnt options

To test the potential impact of installing energy efficiency measures in the base-case house and their interaction with future climate, twenty-two refurbishment scenarios were chosen. This study assumes that each passive measure is installed in a way that maximises its effectiveness. In reality, it is difficult to demonstrate the validity of this assumption. In fact, even apparently small variations from the ideal installation conditions can have a significant role on the real behaviour of different solutions (Gaterell and McEvoy 2005).

In the insulation measures, there are two important variables that are taken into account and that distinguish one solution from another. These factors are the total U-value of the structure considered and the location of the insulation layer. The material used is not important, nor its thickness. The same U-value, in fact, can be achieved with different types of insulation by simply varying their thickness. The three thermal transmittance thresholds refer to two levels of the Italian energy standard (Legge regionale n. 13 del 28 maggio 2007: Disposizioni in materia di rendimento energetico nell'edilizia) and to the PassiveHouse standard. Table 3.4 shows the U-values for each part of the envelope according to the three categories.

The details and the assumed impacts of each measures are presented in the next subsections.

Material	x (m)	c_p $(\frac{J}{kgK})$	λ $(\frac{W}{mK})$	ϱ $(\frac{kg}{m^3})$
Gypsum plasterboard	0.015	1000	0.25	900
Masonry blocks	0.15	840	0.85	1650
Air gap	0.05	-	R = 0.18	-
Brickwork	0.12	800	0.84	1700
Vapour layer	0.005	-	R = 0.21	-
EPS	0.08	1400	0.04	15
External render	0.02	1000	0.5	1300

Table 3.5: External wall insulation materials and properties.

3.2.1 External wall insulation

RC1

The first refurbishment takes into consideration the opaque wall. In particular, an external insulation is applied to all the exterior walls. The U-value achieved with the materials used and their thickness is the one set by the first level of the Italian energy standard, equal to 0.33 $\frac{W}{m^2K}$. In order to have this thermal transmittance value, 8 cm of Expanded Polystyrene (EPS) insulation have been added outside the brickwork. The refurbishment methodology adopted is the wet render system. By putting the insulation outside the wall, condensation occurs in the internal layers of the envelope. for this reason a PVC vapour barrier membrane has been placed on the warm side of the wall. Table 3.5 shows materials, thickness and properties of the adopted solution.

RC2

In the second refurbishment the U-value to reach is the one of the second level of the Italian standard, which is equal to 0.25 $\frac{W}{m^2K}$. This value can be achieved in two ways. The first one is to increase the thickness of the Expanded Polystyrene (EPS) insulation to 12 cm. The second one is to choose a different type of insulation with lower thermal conductivity and use a thinner layer. For example, polyurethane has a thermal conductivity equals to 0.023 $\frac{W}{m^2K}$, and with this material a thickness of 7 cm is needed to achieve the U-value target. Anyway, by choosing the second option, the variation between RC1 and RC2 will not be dealing just with the U-value, but another factor will influence the thermal behaviour of the envelope. In fact, the different density and specific heat of the polyurethane engenders a thermal mass that is lighter than that of EPS. In order to vary just one variable at a time, the insulation, we chose the EPS as solution. The only difference with RC1 is in the thickness of the insulation layer, which is 12 cm instead of 8 cm.

Material	x (m)	c_p $(\frac{J}{kgK})$	λ $(\frac{W}{mK})$	ϱ $(\frac{kg}{m^3})$
Gypsum plasterboard	0.02	1000	0.25	900
EPS	0.08	1400	0.04	15
Vapour layer	0.005	-	R = 0.21	-
Gypsum plasterboard	0.02	1000	0.25	900
Masonry blocks	0.15	840	0.85	1650
Air gap	0.05	-	R = 0.18	-
Brickwork	0.12	800	0.84	1700

Table 3.6: Internal wall insulation materials and properties.

RC3

The third refurbishment deals with the PassiveHouse standard, which implies a maximum heat transfer coefficient of 0.15 $\frac{W}{m^2K}$. To vary just one parameter between the previous refurbishments, in this case the thickness, a 23 cm insulation layer of EPS must installed. This considerable thickness has many drawbacks, such as the necessity to move forward the roof eaves and the openings' sills.

3.2.2 Internal wall insulation

RC4

In this refurbishment too we want to change only one variable in comparison to the other refurbishment solutions. For this reason the same thickness and insulation material as refurbishment 1 has been applied to the wall internally. The refurbishment methodology chosen is the insulated plasterboard, which is the easiest in this case. The materials and thickness used are shown in table 3.6. As shown in the table, in this case too a vapour barrier has been placed in the layers of the wall to prevent condensation inside the layers. The U value reached with 8 cm of EPS insulation is the same as refurbishment 1, i.e. 0.33 $\frac{W}{m^2K}$.

RC5

This refurbishment refers to the second level of the Italian standard, that has to be reached with the internal insulation. The U-value of 0.25 $\frac{W}{mK}$ can be achieved with 12 cm of EPS insulation applied in the internal surface with the insulated plasterboard technique. Materials and properties are the same as RC4 and are illustrated in table 3.6, keeping in mind that the only variation occurs in the thickness of the insulation layer.

Material	x (m)	c_p $(\frac{J}{kgK})$	λ $(\frac{W}{mK})$	ϱ $(\frac{kg}{m^3})$
Gypsum plasterboard	0.015	1000	0.25	900
Roofing felt	0.005	837	0.19	960
Wood rafters	0.10	1420	0.15	600
Mineral wool	0.09	840	0.038	140
Clay tiles	0.025	800	1.00	2000

Table 3.7: External roof insulation materials and properties.

RC6

Refurbishment six deals with internal insulation. It must respect the maximum value of transmittance allowed in a PassiveHouse. The U-value, equal to 0.15 $\frac{W}{m^2K}$, is achieved with 23 cm of EPS insulation. The considerations regarding materials, properties and refurbishment techniques are the same as the other internal wall insulation.

3.2.3 External roof insulation

RC7

The base case house has a pitched roof of wooden rafters without insulation. With the first intervention, insulation is added above rafters and the tiling is renewed. The 9 cm of mineral wool aims for a U-value of 0.30 $\frac{W}{m^2K}$ to meet the threshold of the first level of the Italian standard. Table 3.7 shows the details regarding materials, thickness and properties of the adopted solution.

RC8

In this refurbishment the target to reach is the one set by the second level of the Italian standard. The U-value of 0.23 $\frac{W}{m^2K}$ is reached with the use of the same material as RC7. Only this time the mineral wool has a thickness of 13 cm.

RC9

This is the last case of external roof insulation. For the PassiveHause standard a U-value of 0.15 $\frac{W}{m^2K}$ is achieved with the installation of 22 cm of mineral wool above the rafters.

3.2.4 Internal roof insulation

RC10

This refurbishment solution deals with roof insulation, but this time the mineral wool is applied below the rafters. Table 3.8 shows the materials which are used to reach the

Material	x (m)	c_p $(\frac{J}{kgK})$	λ $(\frac{W}{mK})$	ϱ $(\frac{kg}{m^3})$
Internal gypsum	0.015	1000	0.25	900
Mineral wool	0.09	840	0.038	140
Internal gypsum	0.015	1000	0.25	900
Roofing felt	0.005	837	0.19	960
Wood rafters	0.10	1420	0.15	600
Clay tiles	0.025	800	1.00	2000

Table 3.8: Internal roof insulation materials and properties.

first level of the Italian standard, that is 0.30 $\frac{W}{m^2K}$. The internal insulation is installed under the plaster of the ceiling and then covered with an internal gypsum plasterboard.

RC11

This refurbishment refers to the second level of the Italian standard, that has to be reached with the internal insulation of the roof. The U-value of 0.23 $\frac{W}{m^2K}$ can be achieved with 13 cm of mineral wool applied on the internal surface of the roof. Materials and properties are the same as RC10 and are illustrated in table 3.8, keeping in mind that the only variation occurs in the thickness of the insulation layer.

RC12

Refurbishment twelve is the last case of internal roof insulation. The PassiveHouse recommended U-value, equals to 0.15 $\frac{W}{m^2K}$, is achieved by using 22 cm of mineral wool. The considerations regarding materials, properties and refurbishment techniques are the same as in the previous two subsections.

3.2.5 Floor insulation

RC13

Refurbishment thirteen is about the improvement of the ground floor thermal performances. In order to achieve the first level required by the Italian standard, a U-value of 0.30 $\frac{W}{m^2K}$, it is necessary to install 7 cm of extruded polystyrene (XPS) in the cavity of the suspended floor. The type of measure adopted is the insulation from below. The drawback is that the dimension of the air gap, which is situated under the floor, is reduced. Ventilation is still present and the height of the floor is not modified. Table 3.9 shows the materials used and their thickness and properties.

Material	x (m)	c_p $(\frac{J}{kgK})$	λ $(\frac{W}{mK})$	ϱ $(\frac{kg}{m^3})$
Ceramic floor tiles	0.03	850	0.80	1700
Floor screed	0.07	840	0.41	1200
Wood hardboard	0.05	2000	0.13	900
XPS	0.07	1400	0.03	35
Ventilated cavity	0.13	-	R = 0.09	-
Cast concrete	0.10	1000	1.13	2000

Table 3.9: Internal floor insulation materials and properties.

RC14

In this refurbishment the target to reach is the one set by the second level of the Italian standard. The U-value of 0.23 $\frac{W}{m^2K}$ is reached thanks the use of the same material as RC13, but with a different thickness of 10 cm.

RC15

The PassiveHouse U-value, equal to 0.15 $\frac{W}{m^2K}$, is achieved by using 17 cm of extruded polystyrene insulation. The considerations regarding materials, properties and refurbishment techniques are the same as in the previous two subsections.

3.2.6 Windows substitution

RC16

All the windows of the building have to be changed in order to achieve the first level of the Italian standard, a glazing U-value of 2.0 $\frac{W}{m^2K}$. By substituting all the transparent openings with double glazing windows (Low-E e2=2, clear glass, 6mm/13 mm air) it is possible to achieve a U-value of 1.9 $\frac{W}{m^2K}$. Table 3.2 illustrates the properties of the two panes of glass.

RC17

Refurbishment number seventeen deals with the insulation of the window. This time the U-value to reach is the one set by the second level of the Italian standard. To achieve this target, all the external windows are substituted with double glazing windows with argon (Low-E e2=2, clear glass, 6mm/13 mm argon). In this way, the U-value of 1.7 $\frac{W}{m^2K}$ is achieved.

Structure	Material	x (m)	λ $(\frac{W}{mK})$	SHGC
Single glazing	Clear pane	0.003	0.9	0.47

Table 3.10: Triple glazing windows' materials and properties.

Structure	Material	x (m)	λ $(\frac{W}{mK})$	Distance to glass (m)
Shading system	Venetian blind	0.003	0.1	0.05

Table 3.11: Venetian blinds' materials and properties.

RC18

Refurbishment eighteen is the last case of window insulation. It must respect the maximum value of transmittance allowed in a PassiveHouse, that is equal to 0.80 $\frac{W}{m^2K}$. With the substitution of all the windows with triple glazing windows with argon (Low-E e2 = e5= 1, clear glass, 3 mm/13 mm argon) the U-value reached is 0.78 $\frac{W}{m^2K}$. As shown in table 3.10 the panes of the windows are thinner, and their properties are slightly different from the ones in the previous refurbishments.

3.2.7 Use of shading systems

RC19

Refurbishment nineteen is about avoiding overheating with shadow systems. The solution consider to install internal venetian blinds [2]. Those kind of blinds have been selected because they can also be placed outside the windows whereas normal drapes cannot. In this way, in refurbishment number twenty, there will be only one factor changed, that is the position of the shading system. Table 3.11 shows the properties of the blinds.

RC20

Refurbishment twenty is the last case of shading system installation. The same shading as the previous case, with all its properties, has been modelled in this solution. The only difference is in the location, that this time is outside the windows.

[2] In DesignBuilder, the control type for the shading is the inside temperature, with a set-point temperature of 23°C.

Material	x (m)	c_p $(\frac{J}{kgK})$	λ $(\frac{W}{mK})$	ϱ $(\frac{kg}{m^3})$
Gypsum plasterboard	0.015	1000	0.25	900
PCM gypsum board	0.03	1000	0.25	900
Masonry blocks	0.15	840	0.85	1650
Air gap	0.05	-	R = 0.18	-
Brickwork	0.12	800	0.84	1700

Table 3.12: PCM installation materials and properties.

3.2.8 Use of PCM

RC21

Refurbishment twenty-one deals with the use of PCM.

The type (i.e. melting temperature),the quantity (i.e. thickness) and the installation (i.e. the location of the PCM) of the PCM are relevant factors for proper design of energy saving refurbishments (Ascione et al. 2014). According to Ascione et al. (2014), the biggest energy saving can be achieved by installing the PCM in the internal face of all vertical walls. In that study, the comparison was made between all the internal walls, the only internal face of South and East façades and the internal face of façades and the roof. In our analysis, 3 cm of PCM are modelled on the inner side of the external walls.

Table 3.12 shows the materials used in this solution, and their properties.

[In DesignBuilder the temperature coefficient is 0.25 $\frac{W}{m^2K}$ and the temperature enthalpy curve has 4 points. We also had to change the simulations parameters. Firstly, we increased the time step from 4 to 12 per hour in order to increase accuracy at the expense of simulation times. Secondly, we used the solution algorithm “Finite difference” to include the effect of material phase change properties in simulations. If, instead, the CTF algorithm is used, the material will behave as if its PCM option were not selected. Finally, the inside face surface temperature convergence criteria is set to “0.01” to increase accuracy, again at the expense of simulation times.]

3.2.9 Envelope airtightness

RC22

This refurbishment is the only one dealing with airtightness. We changed the crack template of the building from “poor” to “good”. The option “excellent” was not used because of the obsolescence of the base case. This refurbishment, therefore, includes the closure of the major air gaps of the home, but not the installation of an airtight barrier on the envelope.

Chapter 4

The Energy Assessment Methodology

This chapter presents a simulation study that aims to provide a solution for the complex interaction between uncertainty in the future climate and the assessment of different refurbishment solutions. This initial work focuses on a domestic dwelling in Europe and on refurbishment, but the same methodology could be extended to all kind of buildings, different climates and new construction.

The performance aspect selected in our evaluation methodology is *energy usage*, a parameter which is influenced by many factors. In this study we focus on the effects produced by uncertain climate conditions in future years and by the different thermal properties of the building envelope due to refurbishment solutions. In order to provide occupants thermal comfort [1], the energy usage varies according to the outside temperature and to the envelope properties.

We will describe a methodology to assess how the energy outcomes of refurbishment measures, which alter the thermal characteristics of a dwelling, are sensitive to future climate variations. That is, to assess how the energy usage calculated will be influenced by unaccounted temperature variations due to climate change, and by changing the thermal properties of the building envelope, due to refurbishment measures.

This study examines how decisions made today regarding refurbishment solutions need to be considered in light of projected climate change. So far, the assessment of different solutions is done with a current weather file without taking into account future climate variations. In some other studies (Gaterell and McEvoy 2005; Holmes and Hacker 2007) authors include future climate changes but rely on a single set of weather file as the *sole* representation of the future. Thanks to the capabilities of modern computers it is possible to run the same simulation numerous times, with different future weather files without worrying about computational time. In this way, it is

[1] In this case, thermal comfort refers to fixed internal temperatures, which are a maximum of 26° C in summer and a minimum of 20° C in winter.

possible to assess the robustness of different refurbishments in terms of energy usage, taking into account various future scenarios.

In the following paragraphs we explain how we calculate the energy performance of a building and how this is useful in the assessment of the robustness of dwelling to climate change.

4.1 Energy Performance of Building

Before going any further in the description of the study, it is necessary to clarify the meaning of some terms related to energy. The energy in a building can be described from four different perspectives (Richarz and Schulz 2013). The first three refer to the energy itself at different stages in its way from generation until consumption in the building, while the last one is related to the production of CO_2 due to energy usage. In this section, we briefly explain the difference between the three energy terms, without discussing the CO_2 production because it is not strictly related to our analysis.

The easiest energy to calculate in a building is the *energy consumption*, or energy need, or effective energy. *It is the heat to be delivered to, or extracted from, a conditioned space by a heating or cooling system to maintain the set-point temperature during a given period of time for occupants' comfort (UNI EN ISO 13790).* Usually this is the quantity calculated by energy tools and by thermal equilibrium analysis, and it is also referred as ideal or thermal loads. The total effective energy in a building is due to heating, cooling and lighting. There are different variables that influence this energy, such as the thermal comfort conditions, the useful floor area, the compactness of the building, the external temperature and the quality of the building envelope. We will focus on the the last two variables, changing the external climate both in time and in space, and the thermal performances of the envelope with different refurbishments. The other variables will not change because the building shape will be the same for all the simulations and so will the thermal comfort boundaries. Sometimes, this kind of energy is incorrectly called energy demand. In reality, energy consumption and demand are two related, yet different, measurement parameters. The first refers to the quantity of energy to add or remove in a space, as explained before. The latter is the immediate rate of that consumption, i.e. the power at a particular instant in time. For this reason, energy usage is measured in kilowatt hours (kWh), whereas the rate of consumption –the energy demand– is measured in kilowatts (kW).

The second term related to energy is the *final energy* or energy usage. *It is the amount of energy that is supplied to the building and that is necessary to run the generator of cold and heat.* There are many types of losses associated with each conversion as energy is moved from generation into a room. These losses are related to the type of power generation, the storage, the distribution system and the output. For example, in the case of heating, energy losses occur via heat losses through the boiler, the hot water

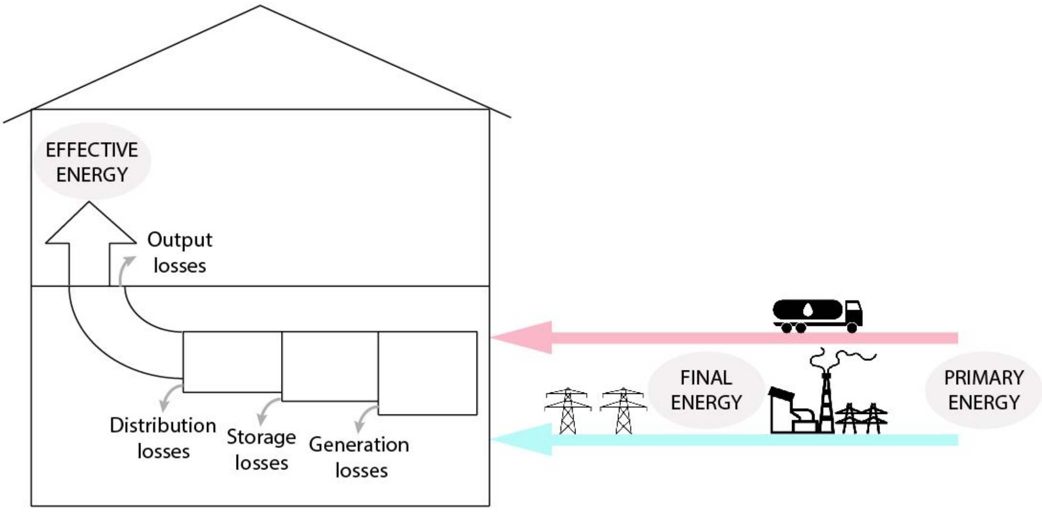


Figure 4.1: Energy losses from generation to distribution in the dwelling (in red the heating, in blue the cooling).

storage, the distribution pipes and the thermostatic valves. Also the energy used to operate technical equipment (e.g., pumps, fans) contributes to the final energy figure and this usage is called auxiliary energy.

Particular attention must be paid to the cooling energy consumption. Usually, air-conditioning units are electrically driven. This means that in the conversion from energy consumption to final energy it is also necessary to calculate how much (finite) primary sources are required to generate the electricity. In Italy, for example, according to the Italian AEEG, Authority for Electrical and Gas Energy (approval EEN 3/08, 28 March 2008), the performance of the Italian national electric system is equal to 0.46. It means that 1 kWh$_e$ of electricity coming from the public network corresponds to the consumption of 2.17 kWh$_f$ of final energy, i.e.:

$$1 \quad kWh_f = 0.46 \quad kWh_e \tag{4.1}$$

$$1 \quad kWh_e = 2.17 \quad kWh_e \tag{4.2}$$

The last form of energy is the *primary energy. It refers to the energy at the source, which has not been subjected to any conversion or transformation process.* The energy, before reaching a building, has many losses associated with its distribution and production (generation or extraction). Therefore, the final energy has to be corrected and increased by using a primary energy factor, which indicates how much of one or more primary sources have been used in the energy generation process.

Figure 4.1 shows the losses of energy among these three forms from generation until distribution in a room.

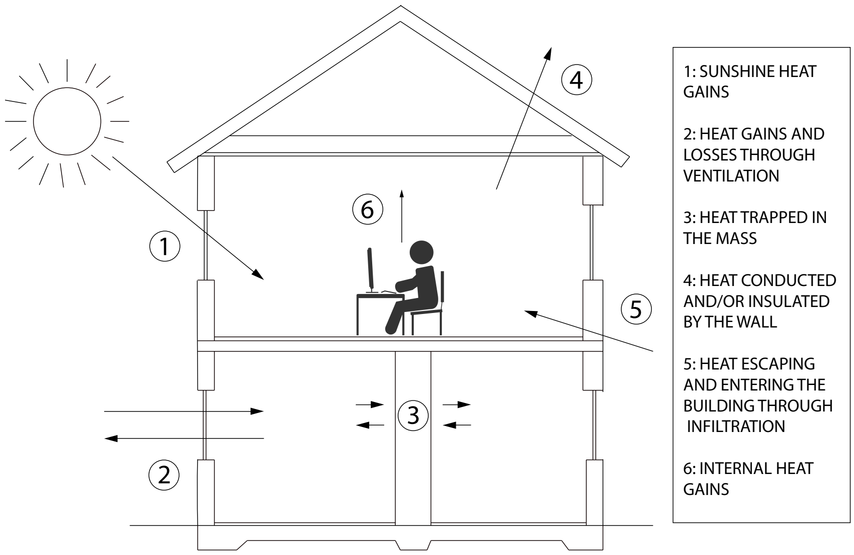


Figure 4.2: Heat flow diagram in a building.

In the following chapters we will use the final energy to compare the thermal performances of different refurbishments in various locations and times. In this way, we will be able to sum the energy used for heating and cooling, referring to the amount of finite resources (e.g., oil, gas, coal) after their production and distribution, until the building in the case of heating and until the power station for cooling.

4.2 Assessment of Energy Performance at Building Level

As mentioned before, we evaluate the thermal performance of an envelope on the basis of the energy usage of the building. The energy usage of a building can be calculated from the energy need, applying upon the proper coefficient of performance. The problem is, therefore, to evaluate the correct (ideal) heating and cooling loads to add or remove from the building to provide the occupants' thermal comfort by maintaining the specified set-point temperatures. Therefore, it is necessary to do a thermal equilibrium analysis.

The main European standards addressing methods for thermal calculation are *EN 832: Calculation of energy use for heating – residential buildings* and *ISO 13790: Energy performance of buildings – calculation of energy use for space heating and cooling.* They are based on energy transfer through the envelope, but neither moisture transfer nor latent heat is considered. The heat transfer is due to transmission, ventilation and the contribution of internal and solar heat gains. Figure 4.2 shows different heat flows. In particular, point one refers to sunshine heat entering through the windows, point two to the heat escaping and entering the building due to ventilation, point three to the

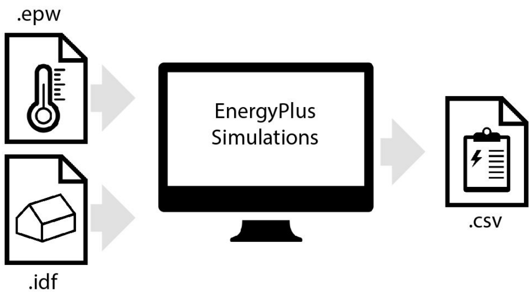


Figure 4.3: EnergyPlus input and output files.

heat trapped into the mass of heavy materials, point four to the heat conducted or/and insulated by the walls, point five to the heat escaping and entering the building due to infiltration, and finally point six to the heat coming from people and devices in the building.

In the appendix we explain a simplified description of thermal simulation based on standard ISO 13790.

4.2.1 Energy simulations

Due to the fact that we need to simulate many refurbishments in different times (present and future) and locations (different latitudes), it is necessary to use a energy simulation tool to calculate the energy need of the building. The complexity of solving temporal/spatial equations, in fact, has led to the development of several building energy simulation programs (e.g. BLAST, BSim, DeST, DOE-2.1E, Sefaira, Ener-Win, Energy Express, Energy-10, EnergyPlus, eQUEST, ESP-r, IDA ICE, HAP, HEED, PowerDomus, SUNREL, Tas, TRACE and TRNSYS). These kind of programs use dynamic thermo-energetic methods, which are based on temporal evolution of different "nodes" of the building due to dynamic excitations (i.e weather conditions). These methods, compared to quasi-steady state ones, are generally more precise, allow data analysis for shorter period of time ,i.e. monthly, weekly, daily or on hourly basis and allow the estimation of peak power demands.

In this study, the thermal behaviour of the building is simulated with EnergyPlus Version 8.1. EnergyPlus is a modular, structured code based on the most popular features and capabilities of BLAST and DOE-2.1E (Crawley et al. 2008). It is a simulation engine with input and output of text files, but that can also be used with a user-friendly graphical input interface (GUI), such as DesignBuilder. By using a GUI it is possible to create the building model in an easier and more intuitive way. Figure 4.3 summarizes the input and output files used to calculate the thermal performance of the building with EnergyPlus. The two input files are the IDF files generated by DesignBuilder, which contains the details regarding the thermal model, and the EPW

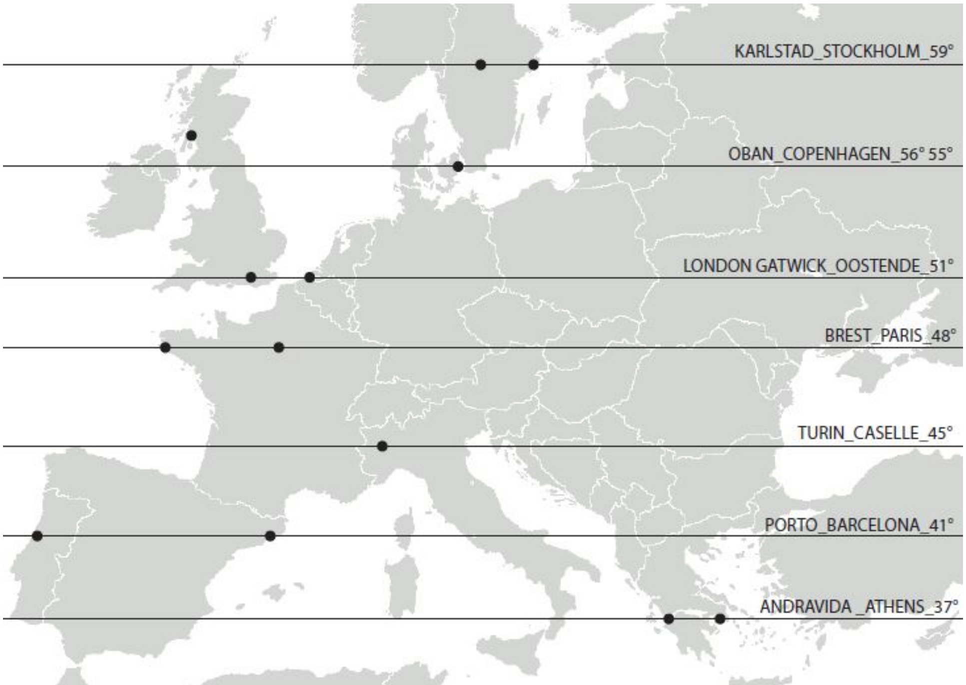


Figure 4.4: Latitudes and cities chosen in the analysis.

files referring to the climate conditions, which will be explained in the next section. EnergyPlus simulations produce hourly results in comma separated files (.csv "comma separated values") that can be read as texts or as spreadsheets. In our analysis the results that we want to elaborate are under the output label "Zone Ideal Loads Supply Air Total Cooling/Heating Energy", which indicates the district heating and cooling energy consumed by the ideal loads system to heat and cool the air supply. The two results referring to heating and cooling must be converted to final energy to be comparable and added together. The software MATLAB was used for the simulation of data, while Excel was used for the elaboration of the final results.

4.3 Cities and Weather Data

We will analyse the thermal performances of the refurbishment solutions in terms of energy consumption by varying their *locations* and *time*.

4.3.1 Cities used in the energy simulations

Regarding the location, the same building models (base case and refurbishments) were simulated at seven different latitudes across Europe, which differ by about 3° from one to the next. Two cities represent each latitude in order to have more data and replicates for each point. The restriction in the choice of the cities is in the weather

Generic latitude	City	Country	Annual average low T	Annual average high T	Annual average total T
37°	Andravida	Greece	22.3	12.5	17.4
	Athens	Greece	22.0	14.3	18.2
41°	Barcelona	Spain	20.0	11.1	15.6
	Porto	Portugal	19.1	19.9	14.5
45°	Caselle	Italy	16.8	6.5	11.6
	Turin	Italy	16.8	6.5	11.6
48°	Paris	France	15.5	7.5	11.5
	Brest	France	14.1	7.6	10.8
51°	London Gat.	UK	13.9	5.2	9.6
	Oostende	Belgium	12.5	6.6	9.5
55°	Copenhagen	Denmark	11.1	5.0	8.0
	Oban	UK	12.1	5.0	8.6
59°	Stockholm	Sweden	10.0	3.5	6.7
	Karlstad	Sweden	9.9	2.6	6.3

Table 4.1: Average temperatures of the cities (source: www.climatedata.eu).

stations, which are not present everywhere. During the decision of the second city per latitude, the second parameter which was taken into account was the temperature. The "twin cities", in fact, beside being at the same latitude, have about the same average high temperature, average low temperature and overall average temperature. Figure 4.4 shows that the "twin cities" are Athens and Andravida, Barcelona and Porto, Turin and Caselle, Paris and Brest, London Gatwick and Oostende, Copenhagen and Oban, Stockholm and Karlstad. It can be noticed that Turin is the only city with two weather stations. Moreover, Athens, Paris and Stockholm have the twin city in the same country, whereas Barcelona and London in a close one, in order not to have too different longitudes. The only city that does not have a replicate at exactly the same latitude is Copenhagen. The difference of 1° of latitude between Copenhagen and Oban might causes some difference in the results. In this way it will be possible to see if the latitude is a good representation of a climatic zone. Table 4.1 shows the details regarding the temperatures of each city.

4.3.2 Weather files used in the energy simulations

We run each model with eighteen weather files, which differ in time, future climate scenario and weather source. The weather files refer to the present and to three "eras" in the future (2020's, 2050's and 2080's). The different scenarios are related to the future projections discussed in chapter 1. In this study we will use three scenarios, A2, A1B and B1. The sources refer to the website and software from where we obtained the weather files, which are the U.S. Department of Energy website and the METEONORM software. The U.S. Department of Energy makes available weather data for more than 2100 locations in EnergyPlus weather format. This is a text-based format derived from the Typical Meteorological Year 2 (TMY2) weather format. The Typical Meteorological Year 2 (TMY2) consists of months selected from individual years and concatenated to form a synthetic year to represent the temperature, solar radiation, and other variables within the period of record. It is in contrast with the Test Reference Year-type (TRY) weather data that represent a single year, and which is not suitable to represent the typical long-term weather patterns [2]. The Typical Meteorological Year 2 (TMY2) and therefore the EnergyPlus weather format (.epw) more closely match the long-term average climatic conditions compared to the Test Reference Year-type (TRY). The weather data provided on the website are derived from twenty sources. Referring to our locations, just two sources will be used. The first one refers to all the cities, beside Caselle, and is the International Weather for Energy Calculations (IWEC) [3].

The second source is the Italian Climatic data collection "Gianni De Giorgio" (IGDG), which is used only for Caselle [4].

On the other hand, weather files for specific locations can be downloaded in EnergyPlus format from the Meteonorm software. Meteonorm is a comprehensive meteorological reference database. It generates hourly data from statistical data for many location in the world. Where statistical data aren't available, Meteonorm interpolates from other nearby sites.

Figure 4.5 shows the eighteen weather files used in our analysis. The starting point is the acquisition of three weather files for each latitude, which refer to the present climatic conditions. Two of the three files were downloaded from the U.S. Department of Energy website and the other one obtained from Meteonorm.

[2] Source: EnergyPlus website

[3] The IWEC data collection is the result of ASHRAE Research Project 1015 by Numerical Logics and Bodycote Materials Testing Canada for ASHRAE Technical Committee 4.2 Weather Information. The files are derived from up to 18 years of DATSAV3 hourly weather data originally archived at the U. S. National Climatic Data Center. The weather data is supplemented by solar radiation estimated on an hourly basis from earth-sun geometry and hourly weather elements, particularly cloud amount information (ASHRAE 2001)

[4] The IGDG data collection is developed for use in simulating renewable energy technologies, and has a set of 66 weather files based on a 1951-1970 period of record. The data were created by Professor Livio Mazzarella, Politecnico di Milano, and are named in honor of Gianni de Giorgio.

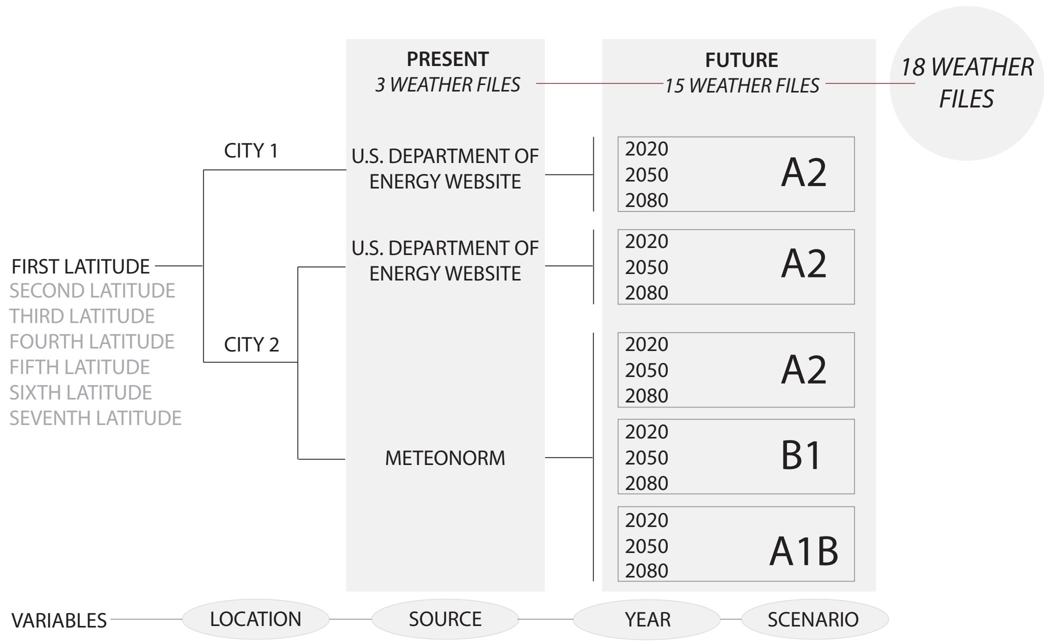


Figure 4.5: Generation of weather files for present and future.

In order to obtain weather files referring to the future, we used two different software. The first one is the software "CC WorldWeatherGen Climate change world weather file generator" [5]. It is a Microsoft® Excel based tool which generates climate change weather files for world-wide locations. It transforms "present-day" .epw weather files into future .epw weather files by using the Third Assessment Report model summary data of the HadCM3 A2 experiment ensemble IPCC 2013. The HadCM3 A2 summary data is provided by the IPCC Data Distribution Centre as monthly values for each grid point of the HadCM3 data grid for a simulated 1961-1990 baseline climate and for three future time slices, the 2020's, 2050's and 2080's. However, monthly data is not suited for use in building performance simulation where hourly data is required. Therefore, the CCWorldWeatherGen tool transforms this data into hourly time series. This is achieved by applying the so-called "morphing" methodology, which was developed by Belcher, Hacker and Powell for UK RCM model results (Belcher et al. 2005). Figure 4.5 shows that with this software it was possible to generate six future files, starting with the two "present-day" .epw files downloaded from the U.S. Department of Energy website, for the 2020's, 2050's and 2080's.

The second software used to generate climate change weather files is Meteonorm. It can be used to generate future weather data accounting for climate change if historical

[5] Version 1.8 provided by the University of Southampton.

monthly averages that are normally used as inputs are replaced with results from a GCM (Robert and Kummert 2012). From all 18 public models of the IPCC AR4, an average has been made at a resolution of 1°. With the combination of Meteonorm's current database from 1961-90, the interpolation algorithms and stochastic generation, future climate can be calculated for any site, for different scenarios (B1, A1B and A2), and for any period between 2010 and 2200 (Remund 2010). Figure 4.5 shows that, in our case, the "present-day" .epw file of Meteonorm referring to one city is the input file for the generation of nine future weather files, which refer to three scenarios (B1, A2, A1B) and three future time slices (2020's, 2050's and 2080's).

To summarize, figure 4.5 illustrates that, for each latitude, the eighteen total weather files differ according to three variables, that are the source (Meteonorm and U.S. Department of Energy website), the year (present, 2020, 2050 and 2080) and the scenario for the future (A2, B1 and A1B). All these weather files are used to simulate the thermal behaviour of each model, both base case and the refurbishments. They represent a range of *possible* climate scenarios in the future. Also the *present files* are considered *possible future climate* with the assumption that the climate will be stable in the future.

From now on we will refer to the files downloaded from the U.S. Department of Energy website and to the related future files as $E+$ and the files obtained with Meteonorm as MN. In table 4.2 we summarize the cities at the same latitude which host the weather stations and some of their features related to their sources i.e., the latitude, the longitude, the altitude and the year of record of the data.

4.4 Unreliability of Weather Data

The eighteen weather files previously described should produce a similar output in EnergyPlus simulations in terms of energy consumption. As stated in the first chapter, climate change projections are affected by many uncertainties and so do the weather files which describe these changes. In order to assess the weather files that we will use, we did a preliminary simulation study with the base case building model and with some weather files from E+ and MN. As mentioned before, these weather files are different because of three main variables, which are the source, the year and the scenario. By adding a different city on the same latitude, the difference of weather station could also be considered a variable for the weather files.

Figure 4.6 summarizes the two preliminary simulations run before starting the robustness analysis, to assess the reliability of the input weather files. The left-hand part of the figure shows that, as a first analysis, the source and the station variables are assessed by simulating the base case with weather files coming from six stations and two sources, referring only to the present. The right-hand part of the figure illustrates that, as a second analysis, the source, the year, and the scenario variables are assessed

Generic latitude	City	Latitude	Longitude	Altitude	Source	Year
37°	Andravida	37.92	21.28	12	E+ (IWEC)	1999
	Athens	37.92	23.73	115	E+ (IWEC)	1982
	Athens	37.92	23.73	15	MN	2005
41°	Barcelona	41.28	2.07	6	E+ (IWEC)	1984
	Porto	41.23	-8.68	73	E+ (IWEC)	1993
	Barcelona	41.4	2.10	175	MN	2005
45°	Caselle	45.18	7.65	282	E+ (IGDG)	2005
	Turin	45.22	7.65	287	E+ (IWEC)	1986
	Turin	45.18	7.65	282	MN	2005
48°	Paris	48.73	2.40	96	E+ (IWEC)	1996
	Brest	48.45	-4.42	103	E+ (IWEC)	1986
	Paris Montsouris	48.80	2.30	75	MN	2005
51°	London Gatwick	51.15	-0.18	0.62	E+ (IWEC)	1991
	Oostende	51.20	2.87	5	E+ (IWEC)	1989
	London Gatwick	51.15	-0.18	0.59	MN	2005
55°	Copenhagen	55.63	12.67	5	E+ (IWEC)	1984
	Oban	56.42	-5.47	4	E+ (IWEC)	1994
	Copenhagen Taastrup	55.70	12.30	28	MN	2005
59°	Stockholm	59.65	17.95	61	E+ (IWEC)	1984
	Karlstad	59.37	13.47	55	E+ (IWEC)	1995
	Stockholm	59.65	17.95	61	MN	2005

Table 4.2: Cities and details related to the source.

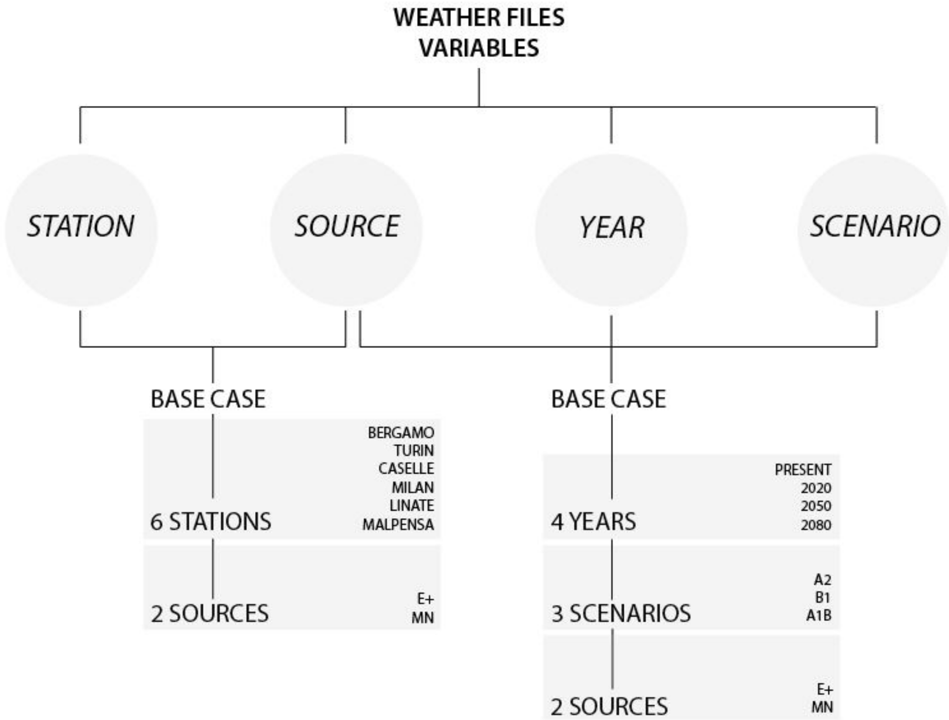


Figure 4.6: Variables influencing the weather files.

by running a simulation with the base case together with weather files coming from one city, two sources and referring to four years and three future scenarios.

In the following subsection we will describe the simulation results regarding the assessment of weather files to describe how the weather files we will use are affected by uncertainties.

4.4.1 Source and station

The first analysis focuses on the influence of weather files from different sources and stations in terms of energy usage. We run the simulation by using the base case building model and focusing only on the present. The stations to which we refer are in the North of Italy and are close in terms of latitude and longitude. Table 4.3 shows that all the stations are situated at the 45° of latitude and their longitudes range from 7.65° to 9.70°.

Figures 4.7 and 4.8 display the six stations on the x-axis and the energy usage in kWh/m^2 on the y-axis, one for heating and one for cooling. The two sources are indicated with a circle and a cross. Table 4.3 shows that the stations can be considered in the same climatic area [6], but the results of the simulations demonstrate that there

[6] It is not always the case that weather stations that are close are in the same climate zone. In this case, however, there are no major geographical features in between these stations. See 4.4

City	Latitude	Longitude	Altitude	Source	Year
Bergamo	45.67	9.70	238	E+ (IGDG)	2005
	45.66	9.70	237	MN	2005
Milan	45.62	8.73	211	E+ (IWEC)	1991
	45.47	9.2	98	MN	2005
Milan Malpensa	45.62	8.73	211	E+ (IGDG)	2005
	45.61	8.73	211	MN	2005
Milan Linate	45.43	9.28	103	E+ (IGDG)	2005
	45.43	9.28	103	MN	2005
Turin	45.22	7.65	287	E+ (IWEC)	1986
	45.18	7.65	282	MN	2005
Turin Caselle	45.18	7.65	282	E+ (IGDG)	2005
	45.18	7.65	282	MN	2005

Table 4.3: Cities in North of Italy and details related to the source.

are difference in terms of energy usage. For the heating, the difference between the results from the two sources is always between 27% and 31% of the highest energy usage, and only in the case of Turin it is 13%. Moreover, the E+ results are always higher than the MN ones. On the other hand, for the cooling, the difference between the two stations is not so neat and constant. In this case, in fact, the MN results are not always higher than the E+ ones, e.g. in the case of Turin. Moreover the difference between the energy usage due to the two sources varies from 31% to 59%, besides Turin, which is 14%. These bigger percentages are due to the fact that energy usage for cooling is lower compared to heating, and so is the difference between results. For this reason, even if the difference seems bigger for cooling in terms of percentage, in terms of total energy usage the difference is bigger for the heating. In fact, the difference between the two sources for heating is more than 35 kWh/m^2 on average, while for cooling the maximum difference is 13 kWh/m^2 on average.

The variations between the sources is likely due to different generation algorithms and to different years of record. These latter, in fact, seems to be the same for almost all the files (i.e., 2005's). In reality, the IGDG source is based on weather data recorded between 1951-1970, and 2005 refers to the year in which they have been modified in some parts. The same could have happened for the Meteonorm database.

Beside the differences between the energy usage due to the two sources, figures 4.7 and 4.8 show that there are some other differences too between the stations. In this

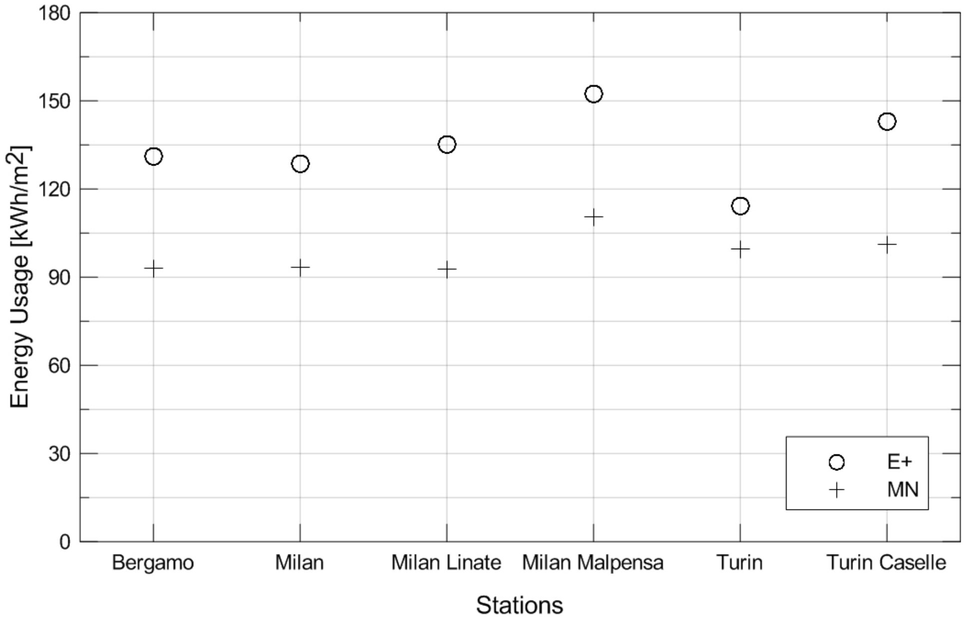


Figure 4.7: results of weather files from different stations and sources in terms of energy usage for heating.

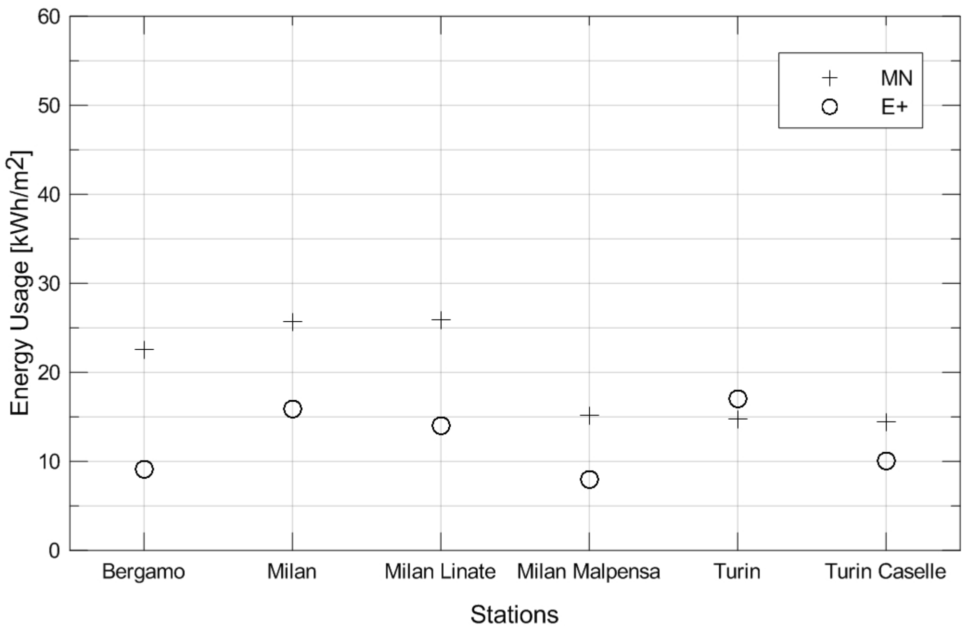


Figure 4.8: Results of weather files from different stations and sources in terms of energy usage for cooling.

case, in fact, the energy usage results should be the same at least for the three stations referring to Milan (Milan, Malpensa and Linate) and for the two stations referring to Turin (Turin and Caselle). In reality figures 4.7 and 4.8 show an anomaly in the case of Malpensa and Caselle, in comparison with the overall average of the results and with the other closer stations. Due to the fact that the weather files are influenced by many factors, it is not easy to evaluate which result is correct, if the anomaly is in Malpensa and Caselle stations or in the others.

Weather files coming from different sources and stations, therefore, have an intrinsic variability which can neither be predicted nor avoided. The error that occurs in the present files generates even higher uncertainties in the projection of future weather files.

4.4.2 Source, years and scenarios

The second analysis focuses on the influence on energy usage of weather files from different sources and referring to different years and future scenarios. In this case, the base case building model has been run only with weather files of the Milan stations, coming from E+ and MN sources. The years considered are the present, 2020's, 2050's and 2080's and the future scenarios are B1, A2 and A1B. The E+ future weather files refer to only the A2 scenario, while MN weather files consider all the aforementioned scenarios.

Figures 4.9 and 4.10 display the 4 years on the x-axis and the energy usage in kWh/m^2 on the y-axis for cooling and heating respectively. The energy usage for heating has a decreasing trend through the years for both sources and the different scenarios, due to the predicted warming of the earth. The difference between the sources, as in the previous simulations shown in sction 4.4.1, are not constant. The lines referring to the two sources, in fact, intersect at different points and are not parallel. The MN data set referring to A2 scenario is the most similar to the E+ one, which is related to the same scenario. The three MN data sets are quite similar and respect the projections of each scenario. The triangular points refer to the less aggressive scenario B1 and for this reason the predicted warming has less impact that the other two scenarios. As a result, the energy usage for heating in the B1 scenario is higher because of the lower global warming.

The difference between scenario MN B1 and E+ A2 is almost negligible around 2050. The same occurs for the scenario MN A2 and MN A1B throughout all years. The difference between these two scenarios and E+ A2 decrease during the period of study, almost reaching the same value in 2080. Figure 4.10 shows that the energy usage for cooling is expected to be higher in the future. The difference between the three scenarios in the MN data sets are especially visible in 2080, when the A2 scenario describes a global warming with more impact than the other two. E+ weather files produce higher energy usage in the future, but not in the present. Both for cooling and for heating the

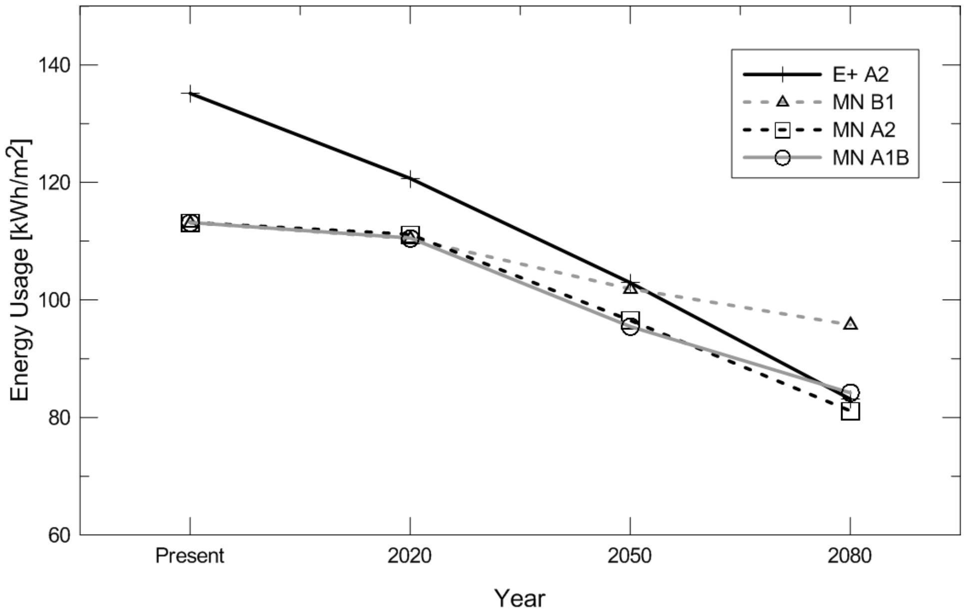


Figure 4.9: Comparison between the influence of weather files from different sources and referring to different years and future scenarios, in terms of energy usage for heating.

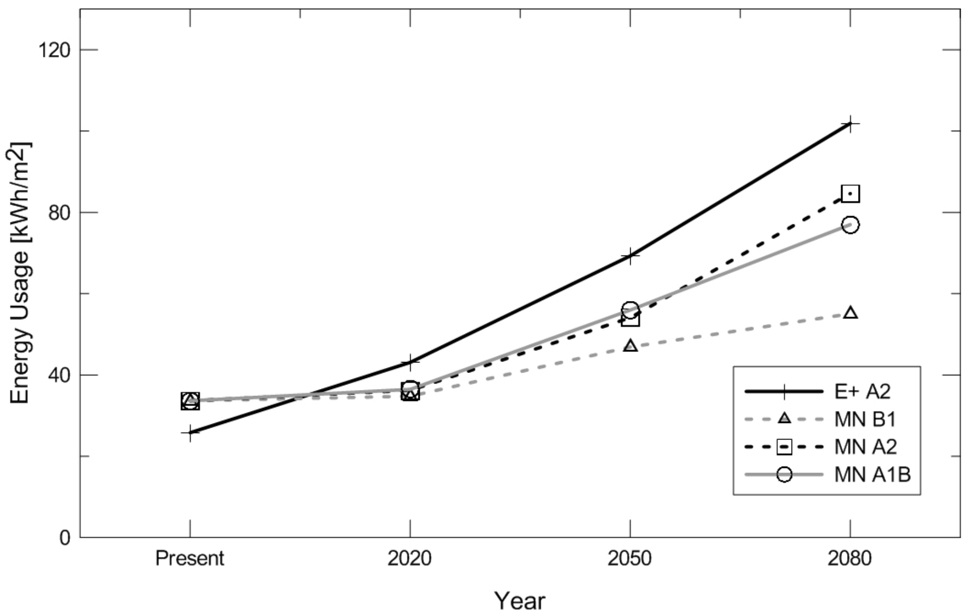


Figure 4.10: Comparison between the influence of weather files from different sources and referring to different years and future scenarios, in terms of energy usage for cooling.

worst projection is made by the E+ weather files, because the energy usage is always higher compared to the MN data sets. The differences in trends between the two graphs means that there is not a linear interaction between the projection for cooling and for heating.

In general, the difference between the energy usage in the future is due to different extrapolation algorithms and to different input data used to generate the future weather files, which we demonstrated to vary even in the present. Due to the fact that the weather files refer to the future, we cannot assess which one is wrong and which one is correct. For this reason, all the input files can be considered as *probable* future projections.

The main conclusion of this two preliminary simulations is that weather files cannot be considered as "duplicates" of the same point, even if they refer to the same climatic area. Instead, they can be considered random inputs, or "replicates" in an experiment of building performance where all other factors remain the same.

4.5 Methodology for Assessing Refurbishment Solutions

In the previous chapters and sections we have illustrated climate change uncertainties, and analysed the variables that influence the weather files used to make projections of the future. We also described the different passive solutions that can be applied in a refurbishment intervention.

At this point we want to illustrate how these refurbishment measures behave in the projected climate scenarios, measuring their performance in terms of energy usage. In most studies on energy assessment of different design choices, building simulations are run referring to current weather conditions without taking into account the predicted global warming that could change remarkably the energy usage in buildings (Kaklauskas et al. 2005; Dascalaki and Balaras 2004; Ascione et al. 2014). Some other studies have been conducted referring to these probable future changes but considering only one input weather file (Frank 2005; Gaterell and McEvoy 2005). Therefore, the majority of building simulations are run with fixed input parameter values and produce results as single values. Design decisions, as a consequence, are influenced by this deterministic approach which likely produce inaccurate or incomplete results. Climate change, in fact, is uncertain itself and, as mentioned before, the weather files that describe these changes are unreliable if considered as single values.

The innovation that we want to introduce in the assessment of building refurbishment solutions is the use of a probabilistic approach to climate change uncertainties. The basic idea is to use different weather files to create a large ensemble of plausible future scenarios, where each member of the ensemble represents one guess about how climate could be. In this way, it is possible to analyse the behaviour of different refurbishment under many plausible future climates. With this project we want to create a new method

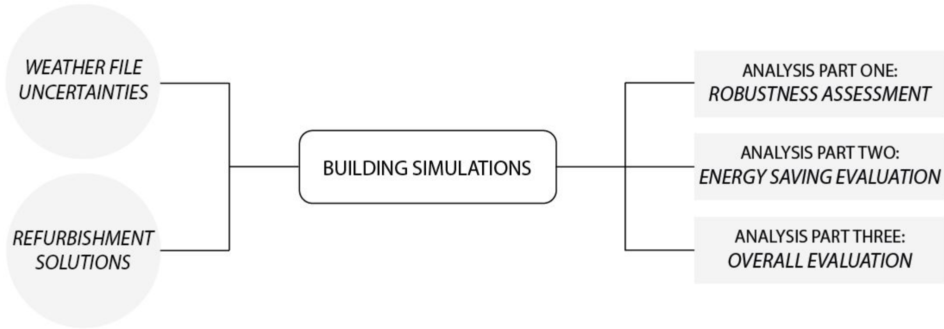


Figure 4.11: Phases of the methodology used in the assessment of different refurbishment solutions.

to help architects and engineers to make better estimates of building performance by considering multiple weather files (and so multiple climates) for both present and future years.

Figure 4.11 shows that, after the simulations, the analysis of each refurbishment solution is conducted in three phases. The first one refers to the robustness evaluation, the second one to the energy saving evaluation and the last one to the sum of the two previous analysis. In this way, the assessment of each refurbishment solution can be evaluated from the points of view of both robustness and energy efficiency.

A brief explanation on the data preparation and on the process followed in the assessment methodology is given in the next chapter. The following sections describe the three parts of the method which are designed to consider the aforementioned issues.

4.5.1 Data preparation

Figure 4.12 summarizes the input and output data for each stage of the study. First of all, for each of the seven latitudes, we use the base case and twenty-two refurbishment cases as building models and eighteen .epw files as input weather files, which consist of different years (present, 2020, 2050, 2080), sources (U.S. Department of Energy website, E+, and the Meteonorm software, MN), future scenarios (A2, A1B, B1) and stations (city1 and city2). From the output files of EnergyPlus we select 414 .csv ("comma separated values") files. In these files the results that we want to analyse are labelled "Zone Ideal Loads Supply Air Total Cooling/Heating Energy", which indicates the district heating and cooling energy consumed by an ideal loads system to heat and cool the air supply. These files are futher processed in MATLAB by adding the heating and cooling loads for each zones and time. The results are two tables, one for heating and one for cooling, in which the energy consumption per year is given. The twenty-three columns of the table indicated the base case or the refurbishment solutions, while the eighteen rows specify the weather file used for the simulations. The

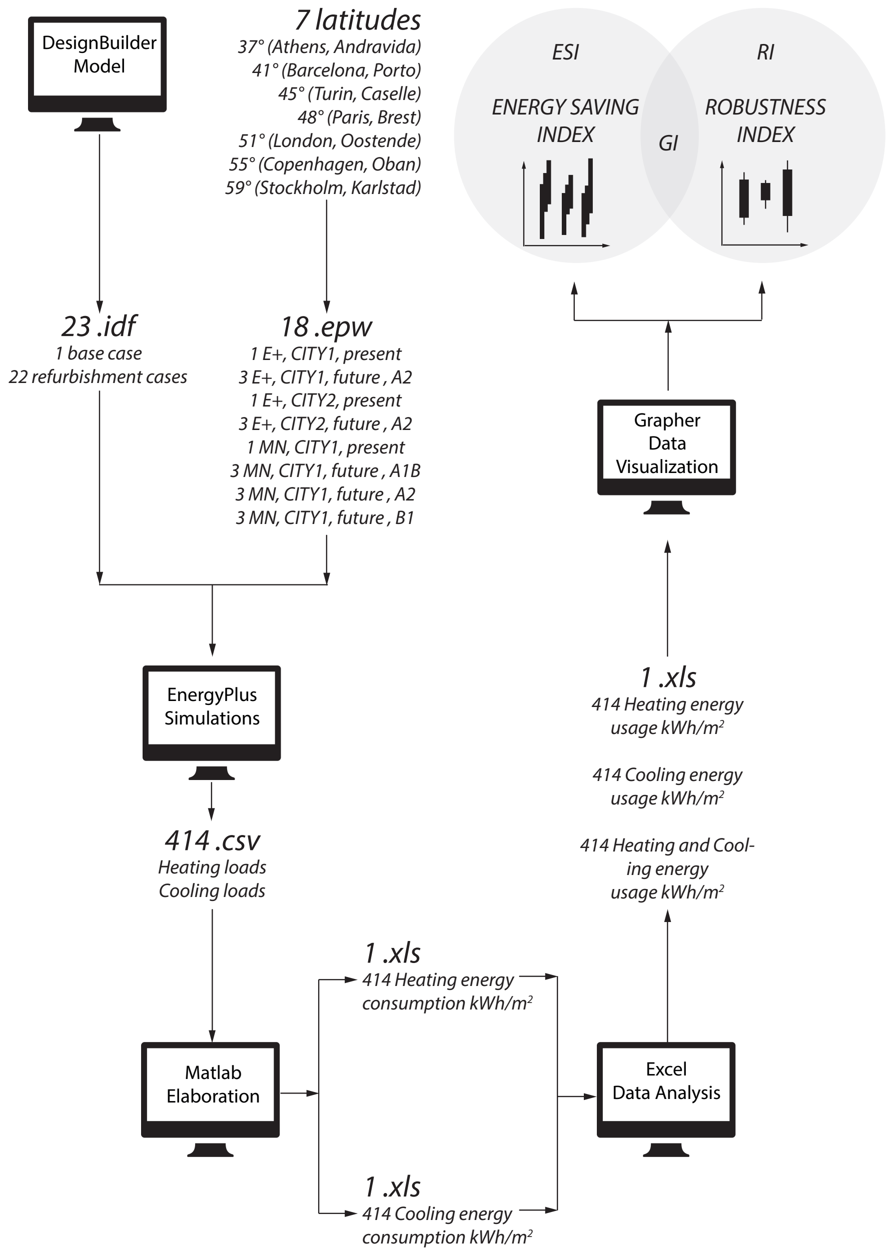


Figure 4.12: Input and output files at each stage of the research study.

values referring to the two types of energy consumption, one for heating and one for cooling, need to be transformed into energy usage to be comparable. In order to do that, a linear transformation must be applied to convert the energy consumption of heating into energy usage, taking into account the efficiency of the condensing boiler. For the cooling consumption two linear transformations must be applied. In fact, the energy consumption for cooling refers to electricity usage (kWh$_e$) due to the fact that the cooling system used in the building (an air conditioning split system) uses electrical energy. The values, after the conversion which take into account the energy efficiency ratio of the system (EER), need to be converted into final energy, which is the same as the heating system. These are the equations used to have comparable values of cooling and heating energy:

$$1Q_H\,(CH) = \frac{1Q_H}{\eta}\,(kWh_{FH}) = \frac{1Q_H}{0.9}\,(kWh_{FH}) \tag{4.3}$$

$$1Q_C\,(kWh_{CC}) = \frac{\frac{1Q_C}{EER}}{0.46}\,(kWh_{FC}) = \frac{\frac{1Q_C}{3.2}}{0.46}\,(kWh_{FC}) = \frac{1Q_C}{1.47}\,(kWh_{FC}) \tag{4.4}$$

where:

- Q_H is the zone ideal loads supply air total Heating energy (output of EnergyPlus simulations)

- Q_C is the zone ideal loads supply air total Cooling energy (output of EnergyPlus simulations)

- kWh_{CH} is the measurement unit of the energy consumption for Heating

- kWh_{CC} is the measurement unit of the energy consumption for Cooling

- kWh_{FH} is the measurement unit of the final energy for Heating

- kWh_{FC} is the measurement unit of the final energy for Cooling

- η is the efficiency of the heating system (condensing boiler, 4 stars)[7]

- EER is the Energy Efficiency Ratio of the cooling system (air split system, class A)[8]

- 0.46 is the performance of the Italian national energy system [9].

Figure 4.13 shows where to apply the linear transformation to convert the energy consumption for heating and cooling in energy usage.

After the generation and elaboration of the data for cooling and for heating and the conversion into final energy, it is possible to start the energy assessment procedure.

[7] The Boiler Efficiency Directive 92/42/EEC.

[8] Italian standard UNI/TS 11300-2.

[9] According to the Italian AEEG, Authority for Electrical and Gas Energy (approval EEN 3/08, 28 march 2008), the performance of the Italian national energy system is equal to 0.46. The value to use in order to convert the electric energy for cooling into final energy is:

$$1kWh_F = 0,46kWh_e \quad or \quad 1kWh_e = 2,17kWh_F \tag{4.5}$$

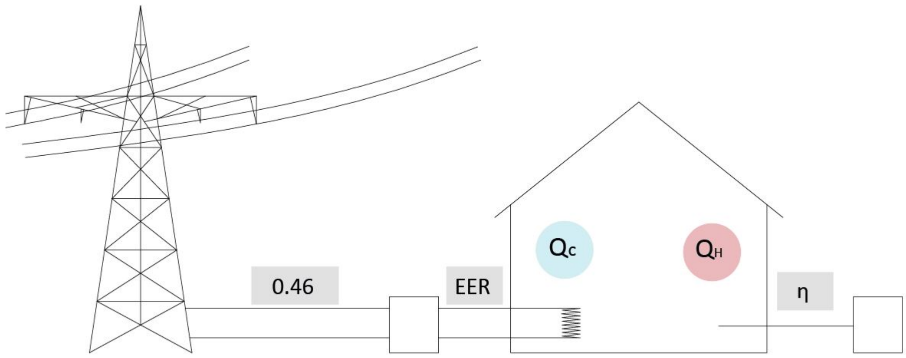


Figure 4.13: Input and output files at each stage of the research study.

4.5.2 Analysis part one: Robustness evaluation

The first part analysis of the methodology is focused on the total energy usage of different refurbishment solutions. The final goal is to assess the refurbishment in terms of robustness to climate change.

The problems that we want to address and solve are:

- How buildings behave in future climate
- How to assess the robustness of a particular refurbishment solution
- How to identify which solution is better in terms of robustness to climate change

The first problem is the easiest to solve, at least theoretically. It is possible to calculate the energy usage of a particular building in any climate condition. However, these results are not completely reliable due to the intrinsic uncertainties of the weather files used as inputs as discussed in paragraph 4.4. We will address the others two problems by using these uncertainties related to future climate scenarios. A *robust solution* should, in fact, *be insensitive to climate change uncertainties.* In practical terms, we want to consider all the eighteen weather files that we have as the projection of future weather climates that could potentially happen in a "general future". This fact means that, in this part of the analysis, it is not important if a weather file refers to a particular year or a particular scenario. The climate changes that the weather files predict are considered possible to the same degree. For this reason, the weather files referring to the present are considered in the robustness evaluation as well because they describe a possible stable climate. By considering all the weather files we have, a refurbishment solution is robust if the range of variation of energy usage is small. In other words, thanks to particular thermal properties of the envelope, the energy usage will be the same or will have little variations in many possible future climates.

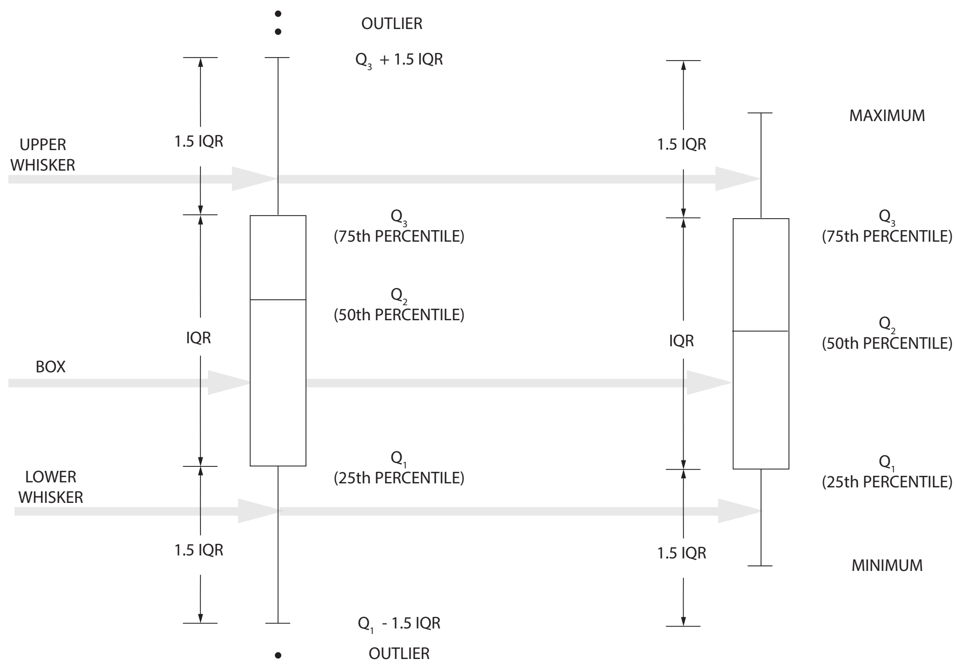


Figure 4.14: The box whisker plot in two different configuration of the whiskers.

The box whisker plots provide a useful way to compare distributions between several groups or sets of data without making any assumptions of the underlying statistical distribution. They use the quartiles of a group of data in order to analyse the distribution of the response to particular variations. The body of the box whisker plot consists of a "box" (hence, the name), which goes from the first quartile (Q_1), or 25th percentile, to the third quartile (Q_3), or 75th percentile. Their difference is called interquartile (IQR) and is represented by the equation Q_3 - Q_1. The line inside the box represents the second quartile (Q_2), or 50th percentile, which is the median of the distribution. The vertical lines (called whiskers) represent the variability outside the first and third quartiles and have two meanings. In general, they are the lowest datum still within 1.5 IQR of the lower quartile (Q_1), and the highest datum still within 1.5 IQR of the upper quartile (Q_3). This means that the whiskers represent the minimum and maximum of the data set if they are included in an arbitrary range based on the quartiles. If some values of the data set are higher or lower than the interquartile, the whiskers represent the boundary of the interquartile multiplied by 1.5 and subtracted from and added to the first and third quartile respectively. In this case, the values higher or lower than the whiskers are considered as outliers and are plotted separately. Figure 4.14 shows the two meanings of the whiskers, on the left when there are outliers and on the right when the whiskers are the maximum and the minimum of the distribution.

In our analysis, box whisker plots represent the base case and the twenty two refurbishment solutions. The boxes and whiskers for each thermal model, include all the energy usage from the eighteen weather files. The robustness of a particular refurbishment can be assessed with the dimension of the boxes. If the box is wide, the response of the building to climate changes varies substantially and, therefore, the particular refurbishment solution is not insensitive nor robust to climate variations. On the other hand, if the box is short, the thermal properties of the envelope make the building insensitive and robust to climate changes, no matter which climate and scenario there will be. In statistical terms, if the dispersion of the data around a certain value is small, the given strategy has a great robustness to climate variability because its thermal performance is stable.

The final results of this first part of the analysis are three box whiskers plots for each latitude, one for the heating, one for the cooling, and one for the total energy usage.

The box whiskers plots are useful to determine if there are big differences between the cases in term of robustness, but they are not easily readable if the variations are small. For this reason we introduce the Refurbishment Index (RI). The RI permits the evaluation of each refurbishment option by taking into account the width of the box (IQR) and the standard deviation of the refurbishment strategy in comparison with the same parameters of the base case. Before being able to use the RI, it is necessary to test if the set of data is normally distributed around the media. Only if the population is normally distributed, in fact, we can use the mean and the standard deviation to assess the dispersion of the values and calculate the RI.

Creating the Robustness Index (RI)

The process begins with the evaluation of individual values for each case, with respect to the standard deviation and the interquartile range. Each parameter is given a weight and then they are summed. The goal of the weighted sum approach is to give more importance to the dispersion around the mean, which is the standard deviation and determines the actual robustness of the refurbishment solution, by taking into account all the energy usage from all the weather files. The interquartile range, in fact, excludes the future climates that are out of the box. It is in any case useful to consider the interquartile range in the calculation for two reasons. The first one is that it indicates the width of the boxes, hence the dimension of the graphic robustness evaluation. The second reason it that it gives less importance to the outliers of the data set, that in statistical terms, should be less probable.

The individual value for each case is called *comparison number* and it is calculated with the following equation:

$$\omega_i = 0.3 \cdot IQR_i + 0.7 \cdot \sqrt{\frac{\sum_{j=1}^{n} (x_j - \mu_i)^2}{n}} \tag{4.6}$$

where:
- ω_i is the comparison number for the i-case ($\frac{kWh}{m^2}$)
- μ_i is the average energy usage for the i-case ($\frac{kWh}{m^2}$)
- IQR_i is the interquartile range of the box whisker plot for the i-case ($\frac{kWh}{m^2}$)
- x_j is a value of the energy usage for the j-weather file ($\frac{kWh}{m^2}$)

In our analysis, n, which is the number of data for each refurbishment, is eighteen. The computation of the interquartile excludes the outliers and the use of the standard deviation represents the mean difference of all the values from the mean, i.e., the dispersion of data.

The comparison number is calculated for both base case (BC) and refurbished cases (RC). In order to make the results between the seven latitudes comparable, the comparison number of each refurbishment must be normalized with that of the base case. This is the equation used for the calculation of the RI:

$$RI_{RC_k} = 1 - \left(\frac{\omega_{RC_k}}{\omega_{BC}}\right) \tag{4.7}$$

where:
- RI_{RC_k} is the Refurbishment Index for the k-refurbishment (unit-less)
- ω_{RC_k} is the comparison number for the k-refurbishment ($\frac{kWh}{m^2}$)
- ω_{BC} is the comparison number for the base case ($\frac{kWh}{m^2}$)

The higher RI a refurbishment case has, the better the refurbishment is in terms of robustness to climate change. This is because the comparison number measures two parameters that must be small to describe a robust refurbishment solution, the interquartile and the standard deviation. A small interquartile, hence a small box, indicates that the majority of the energy usage is close to the median, and excludes outliers. A small standard deviation affirms that the majority or all the values have a small distance from the average energy usage, i.e., the dispersion of data is small. The comparison number, therefore, must be a small value if the refurbishment is a good solution in terms of robustness to climate change. If this is the case, the comparison number for the refurbishment k is lower compared to the one of the base case. As a consequence the normalized comparison number ($\frac{\omega_{RC_k}}{\omega_{BC}}$) is a small number and the RI is a high value.

The RI is useful to calculate a value which indicates the robustness of a particular refurbishment solution but it is also valuable in the comparison of the thermal performances between the base case and the refurbishments. These are the general rules:

- If $\omega_{RC} > \omega_{BC}$ then RI < 0, which means that the refurbishment solution is less robust than the base case
- if $\omega_{RC} < \omega_{BC}$ then RI > 0, which means that the refurbishment case is more robust than the base case.

The RI can range from $-\infty$ (if the ω_{BC} is quite low and the ω_{RC} is really high) to 1 (best score achievable if the ω_{BC} is quite high and the ω_{RC} is really low). In general, with the energy usage values typical of Europe, the RI ranges from -1 to +1. A negative value indicates that the refurbished building is characterized by more dispersed values for cooling and heating energy usage than those of the base case.

The RI can be calculated for the heating, the cooling and the total energy usage. This latter is useful in the comparison of the same solution at different latitudes to see what global warming means in different climatic conditions and for several refurbishment interventions.

The RI does not take into account the energy usage. A refurbishment could have a high RI value, and so be robust to climate change, but at the same time could have very high energy usage. This could happen if all the values are concentrated around a very high energy usage. For this reason it is necessary to introduce another index which is able to classify the refurbishments in terms of energy usage. The index is described in the following subsection.

4.5.3 Analysis part two: Energy saving evaluation

The second part of the analyses carried out in this thesis consists of the comparison of the refurbishment solutions in terms of energy usage, in particular the energy saving compared with the base case.

A refurbishment is done to improve the thermal properties of the envelope and therefore to save energy. The state of the art in the assessment of different refurbishment options is focused on the energy saving of the refurbished building compared with the not refurbished one, using historical weather data. This method could lead to wrong conclusions in the decision process because future climate changes are not taken into account. What we want to demonstrate in this part is that the predicted global warming could have a strong impact on the energy usage of different refurbishment solutions in the future. In fact, the energy usage is likely to be lower in winter but higher in summer. For this reason, a solution that currently consumes little energy could end up consuming for more in future years, in particular for cooling due to global warming. With this analysis, we want to be able to analyse if the different ranges of energy saving

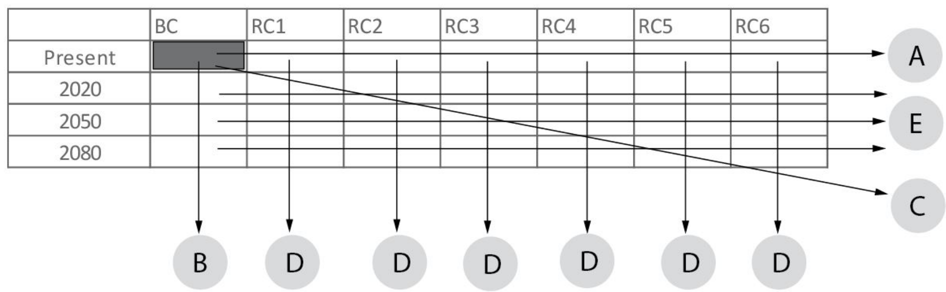


Figure 4.15: Comparisons scheme between energy usage of different refurbishment and in different years.

in future years are constant and, if not, how do they change in time (years) and in space (latitudes).

The questions that we want to address are:

- What is the impact of the refurbishment measures on the base case building in terms of energy usage? Does it increase or decrease?
- What is the impact of the climate change on all the buildings in terms of energy usage? Does it increase or decrease?
- Is the difference between base case and refurbishment cases more influenced by the improvement of thermal properties or by climate change?

All of these questions can be solved by simply subtracting the energy usage of the refurbished case from the one of the base case. The starting point is therefore to understand which results to compare. Figure 4.15 simplifies the data set we have by considering only the base case, six refurbishments and four years (present, 2020, 2050 and 2080). It shows the possible comparison in terms of energy usage between refurbishments and years. Each energy figure, can be considered the result of the interaction between two factors, i.e. the improvement of thermal properties (ΔE_r) and climate change in future years (ΔE_c):

$$\Delta E_{tot} = \Delta E_r + \Delta E_c \tag{4.8}$$

Referring to figure 4.15, one can see that comparison A is the state of the art used today to assess different refurbishments. The first innovation that we want to introduce is the difference between current energy usage for the base case and refurbishment cases in both present and future years. This comparison is indicated with the letter C. Basically, all the energy usage of the refurbishments (in present and future years) are compared with the first cell of figure 4.15, which represents the energy usage today for the base case. The second innovation of this analysis is the identification of the two

		Present		Future	
		BC	RC	BC	RC
Present	BC	identical	A	B	C
	RC	symmetrical	identical	impossible	D
Future	BC	symmetrical	impossible	identical	E
	RC	symmetrical	symmetrical	symmetrical	identical

Figure 4.16: Comparisons matrix between energy usage of different refurbishment and in different years.

parts that constitute the overall energy usage difference calculated with comparison C. As mentioned before, this energy usage difference is composed by a part due to climate change and another one due to refurbishment. With comparisons B and D it is possible to calculate the amount of energy saved (or consumed) due to climate change in future years. With comparison A and E it is possible to evaluate the part of energy saved or consumed due to refurbishment, both in present and in future years. Figure 4.15 illustrates that comparison C also includes comparison B and A. The letters of figure 4.15 refer to the comparison matrix shown in figure 4.16, where all the possible combinations between different refurbishments, base case and years are taken into account.

The *unifying thread* of our analysis is that one set of data in not enough when talking about future weather files. In this part, therefore, we will again use all the eighteen weather files we have to calculate the energy difference between refurbishment cases and the base case, in present and future years. Due to the fact that we will use differences between values, each energy usage in the future will refer to the base case of the same station and source, for comparison C. For comparisons A and E each refurbishment value will refer to the base case value of the same year, source, station and scenario. For comparisons B and D each future value will refer to the the present value of the same station and source.

In this second part we will use histograms to show the energy differences between refurbishment cases (present and future) and the base case in current days, which is comparison C (including A and B). In particular we will use floating bars to show the ranges of energy differences to take into account all the eighteen weather files we have. Figure 4.17 shows that for each case (base case and refurbishments) there will be four floating bars, each of them referring to different years. The bars represent the difference between energy usage for different refurbishments and years in comparison with the base case at present. Therefore the bar referring to base case at current days will always be zero. The bars indicate only the maximum and the minimum difference, without taking into account the distribution of data. Like in the previous comparison, a smaller bar represents a better refurbishment due to little uncertainties related to energy usage.

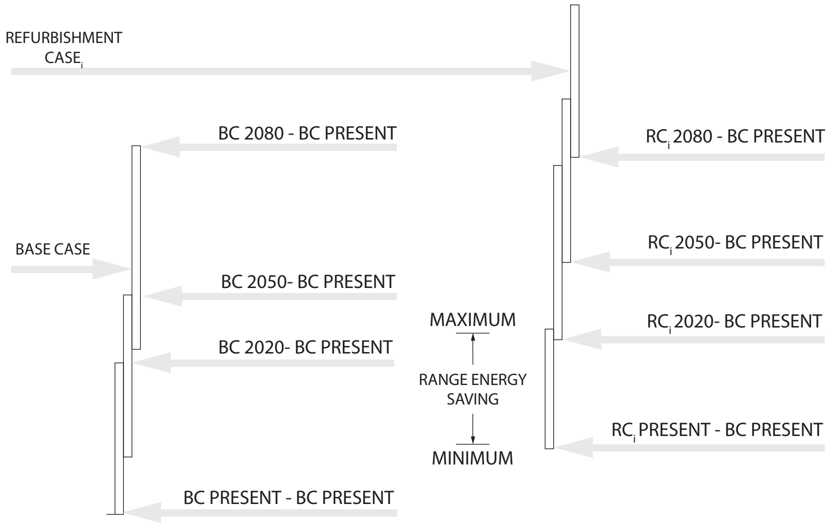


Figure 4.17: Energy difference graph explanation.

However the higher the bars are, the better it is, because they indicate a higher energy saving. These are the steps to follow in order to create the floating bar chart:

- Consider the 414 energy usage values for heating and for cooling after their transformation from energy consumption.
- Create a new table with the results of comparison C ($RC_{future} - BC_{present}$). Each value must be compared only with the value referring to the base case at present of the same station and source.
- Calculate the maximum and the minimum for each year within the eighteen results for each case (base case and refurbishment cases).

Within each bar of the graph, we know that there is a part due to climate change and another one due to refurbishment. We chose to neither show the two parts on the same graph, nor to use two more graphs to show them because of the complexity of the interaction between climate change and refurbishment.

Creating the Energy Saving Index (ESI)

The floating bar chart is useful to understand at first sight the ranges of energy variation in different years and for different refurbishment. Anyway, if the differences between the ranges is small, it is not possible to distinguish one solution from another. For this reason we decided to calculate an index able to classify the different refurbishment measures in terms of energy saving in comparison with the base case. The Energy

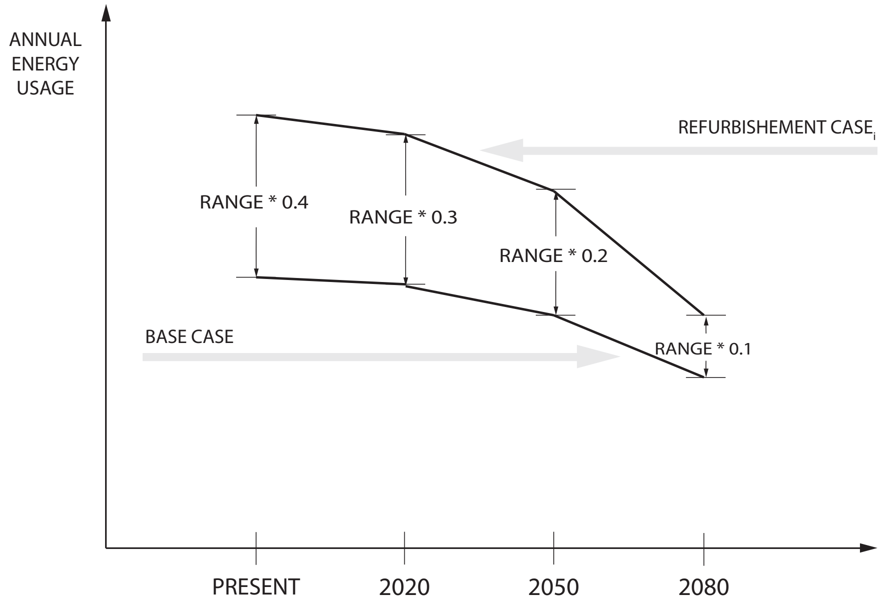


Figure 4.18: Energy saving index explanation.

Saving Index (ESI) is not used to understand which part of the energy saving is due to climate change and which one is due to refurbishment measures, but only to rank the overall energy saving. With this number, therefore, we want to rank in a positive way the refurbishments that save more energy than the base case, whether due to climate change or to the improvement of the thermal properties.

The process begins with the evaluation of a value for each case, with respect to the difference between the energy usage of each refurbishment with that of the base case, in both present and future years.

In this way, each single year of the refurbished case is compared with the same year of the base case (comparisons A and E). Assuming that the weather projections referring to the future years are less accurate the further they are from the present, we decided to use a weighted sum for each term of different years. For this reason, the highest weight is given to comparisons referring to the present and then lower weights are assigned to the other future comparisons. Figure 4.18 shows a simplified schematic graph which illustrates the principle behind the calculation of this comparison number, showing just the base case and one refurbishment case referring to one set of data (same station and source). The real calculations for the comparison number are more complex because they take into account the eighteen values for each case. The average of all the results for each refurbishment is taken into account. In conclusion, the comparison number is calculated with a normalized average of weighted sums of the difference in energy usage between refurbishment cases and the base case. A single weighted sum of the different comparison between years is calculated with the following equation:

$$\vartheta_i = (\sum_{j=1}^{n}(x_{BC} - x_{RC_k})_p \cdot 0.4 + (x_{BC} - x_{RC_k})_{20} \cdot 0.3+ \\ +(x_{BC} - x_{RC_k})_{50} \cdot 0.2 + (x_{BC} - x_{RC_k})_{80} \cdot 0.1)) \cdot \frac{1}{n} \tag{4.9}$$

where:
- ϑ_i is the comparison number of the i-case $(\frac{kWh}{m^2})$
- x_{BC} is the energy usage for the base case $(\frac{kWh}{m^2})$
- x_{RC_k} is the energy usage for the kth refurbished case $(\frac{kWh}{m^2})$
- p, 20, 50, 80 refer to the present, 2020s, 2050s and 2080s respectively
- j is the number of values for each refurbishment(18 in this case).

The Energy Saving Index (ESI) for each refurbishment is the normalization of the comparison number of the refurbishment with respect to the comparison number of the base case. Consequently, in order to normalize each result, ϑ_i must be divided by the same number referring to the base case, where all the x_{RC_k} terms are zero. It is expressed with the equation:

$$\vartheta_{BC} = (\sum_{j=1}^{n}(x_{BC})_p \cdot 0.4 + (x_{BC})_{20} \cdot 0.3+ \\ +(x_{BC})_{50} \cdot 0.2 + (x_{BC})_{80} \cdot 0.1)) \cdot \frac{1}{n} \tag{4.10}$$

The Energy Saving Index, therefore, is calculated with the following formula:

$$ESI_{RC_k} = \frac{\vartheta_{RC_k}}{\vartheta_{BC}} \tag{4.11}$$

where:
- ESI_{RC_k} is the Energy Saving Index for the kth refurbishment (unit-less)
- ϑ_{RC_k} is the comparison number for the kth refurbishment $(\frac{kWh}{m^2})$
- ϑ_{BC} is the comparison number for the base case $(\frac{kWh}{m^2})$

In the calculation of the ESI, the terms ϑ_{BC} can be subtracted from the ϑ_{RC_k} by following this equation:

$$ESI_{RC_k} = \frac{\vartheta_{RC_k}}{\vartheta_{BC}} = \frac{\vartheta_{BC} - \vartheta_{RC_{k0}}}{\vartheta_{BC}} = \\ 1 - \frac{\sum_{j=1}^{n}((x_{RC_k})_p \cdot 0.4 + (x_{RC_k})_{20} \cdot 0.3 + (x_{RC_k})_{50} \cdot 0.2 + (x_{RC_k})_{80} \cdot 0.1)}{\sum_{j=1}^{n}((x_{BC})_p \cdot 0.4 + (x_{BC})_{20} \cdot 0.3 + (x_{BC})_{50} \cdot 0.2 + (x_{BC})_{80} \cdot 0.1)} \tag{4.12}$$

where:

- $\vartheta_{RC_{k0}}$ is the comparison number for the k-refurbishment case when all the x_{BC} terms are equal to zero.

In conclusion, the Energy Saving Index for each refurbishment case is equal to:

$$ESI_{RC_k} = 1 - \frac{\vartheta_{RC_{k0}}}{\vartheta_{BC}} \tag{4.13}$$

where:

- ESI_{RC_k} is the Energy Saving Index for the k refurbishment case (unit-less)

- $\vartheta_{RC_{k0}}$ is the comparison number with the x_{BC} terms equal to zero for the k refurbishment case in different years $(\frac{kWh}{m^2})$

- ϑ_{BC} is the comparison number for the base case in different years $(\frac{kWh}{m^2})$

The higher ESI a refurbishment case has, the better the refurbishment is in terms of energy saving in comparison with the base case. In fact, the comparison number for the refurbishment, which appears in the numerator, is high if a refurbishment saves more energy in comparison with the base case.

The ESI can be calculate for the heating, the cooling and the total energy usage. The last term is useful in the comparison of the same solution at different latitudes to see what global warming means in different climatic conditions and for several refurbishment interventions.

4.5.4 Analysis part three: Overall evaluation

The last part of our analysis is the evaluation of the different refurbishment solutions by taking into account the robustness and the energy saving. Both the RI and the ESI, in fact, describe good performances with larger numbers. It is therefore possible to grade each refurbishment measure with just one number, the Gather Index (GI), which is able to evaluate a refurbishment both in terms of robustness and energy saving. The Gather Index is calculated with the following formula:

$$GI_{RC_k} = \frac{\omega_1 \cdot RI_{RC_k} + \omega_2 \cdot ESI_{RC_k}}{\omega_1 + \omega_2} \tag{4.14}$$

The ω_n indicates the possible weight that can be given to each of the two parts of the GI, depending on what it is considered more important – the robustness property or the energy saving capability. In case no weights are chosen, the GI is the average between the two indices.

In conclusion, the three parts of the analysis are a first step toward recognizing connections between thermal performances of a refurbished building and climate change. In the following chapter a case study will be analysed in depth in order to validate the refurbishment assessment methodology that we developed.

4.6 Methodology Limitations

We want to highlight the fact that our methodology is conducted with just eighteen weather files. Results would be more accurate if a larger sample of weather files is used. The whole process is, in fact, based on statistical approaches that are, strictly speaking, only valid as sample sizes approach infinity. For example, we use standard deviation in our assessment, which is only well-defined (for the formulation we use) for normally distributed data. In any case, using non-parametric estimates of data range like quartiles/percentiles could give absurd results for extremely small sample sizes.

In future work, we propose to extend our methodology to have larger sample sizes.

Chapter 5

Methodology Assessment: a Case Study in Turin

A case study for each latitude has been developed to validate the assessment methodology explained in the previous chapter. In this part, the performance of energy efficiency measures applied retrospectively to an existing residential building will be analysed just for the latitude of Turin. This is the only case, in the seven latitudes we are studying, where the two stations are very close, in terms of latitude, longitude and altitude. The following sections will show how different climate scenarios influence both heating and cooling usage. The first part will explain the state of the art of the evaluation process, in which only one input weather file (present) is needed for simulation. Then, we will show how future years and many different weather files can be used for what is analysed. With the indices and the use of the graphs of our methodology, we will analyse how the use of more than one weather file influences the simulation results. In particular, we want to know if the design choices made referring to just one weather file are different from the ones which refer to a wider range of input weather data.

5.1 State of the Art Analysis of Energy Performance

In the design process of buildings, different measures have to be assessed to make a choice between them and achieve energy targets. According to the state of the art of the evaluation method for different design solution, the measures are assessed in terms of energy performance using just one weather file referring to the current weather. Referring to our comparison matrix shown in figure 4.16, this kind of evaluation is based the comparison A, which calculates the difference in energy usage between the refurbished cases and the base case referring to only the present. Usually, only one weather file is used.

Figure 5.1 shows the energy usage for the base case and the twenty-two refurbished cases we introduced in chapter three. The final energy is calculated using the weather

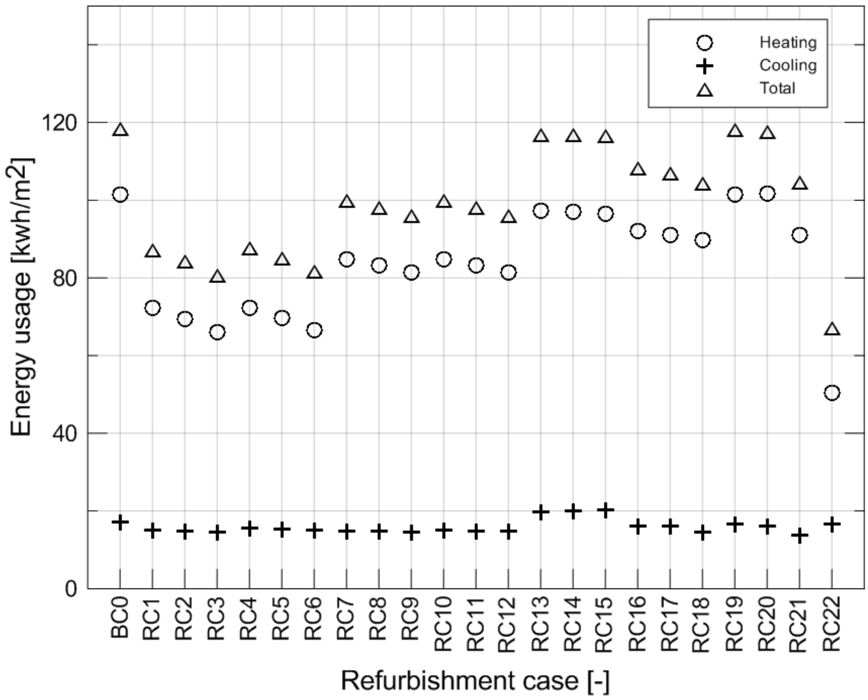


Figure 5.1: Energy usage for cooling, heating and the sum of them, for Turin station (referring to the present and to one source).

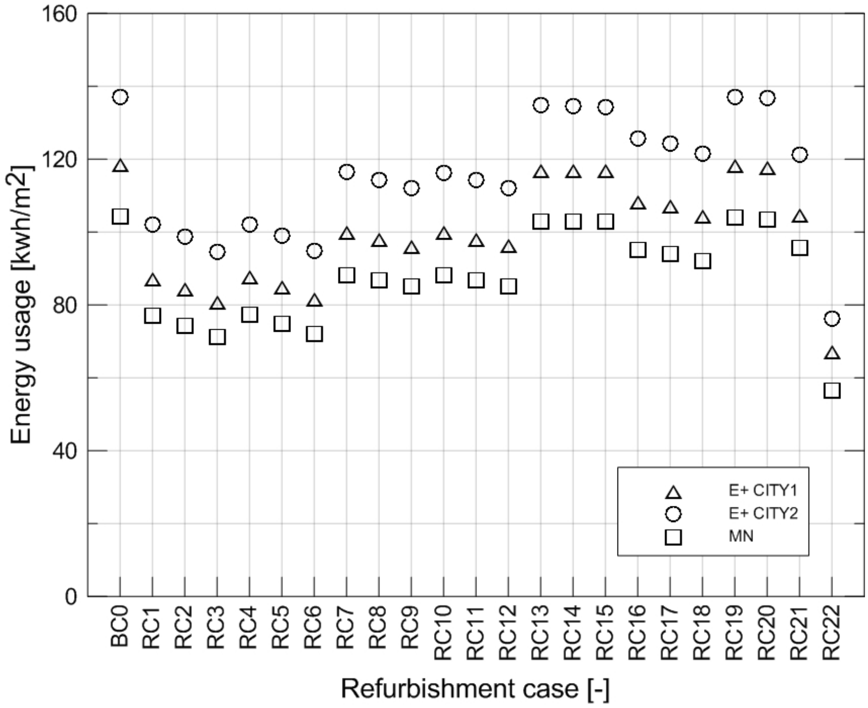


Figure 5.2: Energy usage for cooling and heating, for Turin and Caselle station (referring to the present and to two sources).

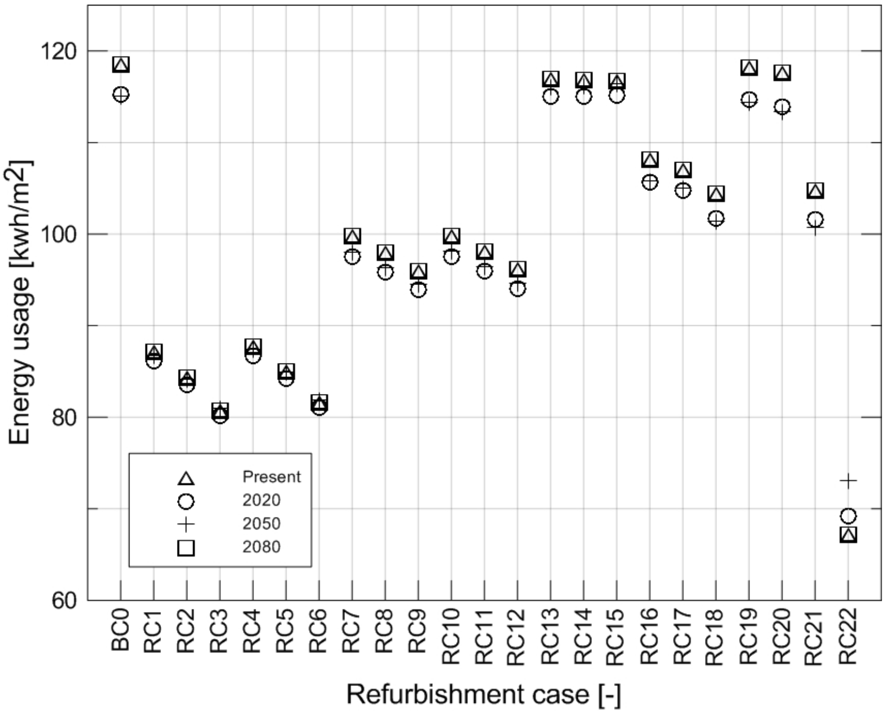


Figure 5.3: Energy usage for cooling and heating, for Turin station (referring to the present and future years and to one source).

file of Turin of the U.S. Department of Energy website, referring to the present. Energy usage for heating, cooling and their sum is shown with different symbols. In the case of Turin, the total energy usage is more influenced by heating energy usage than by cooling. If only this one weather data files were to be used in the design process, refurbishment 22 (decrease infiltration) would be the best solution with just 67 kWh/m^2 of total energy usage compared to the 118 kWh/m^2 of the base case. The second option would be refurbishment 3 (external wall insulation with PassiveHouse standard) with 80 kWh/m^2 of total energy usage.

Figure 5.2 shows the energy usage for the station of Turin and Caselle (CITY1 and CITY2), coming from two sources (MN and E+) and referring to the present. Due to the fact that the data files refer to the same climatic and geographic zone, they should have almost the same results. The graph, instead, shows that the three numbers for each case have different values. However, the ranking of the different refurbishments is the same as with one file (refurbishment 22 is still the best, followed by refurbishment 3). The main difference that can be noticed is the difference between values from the three weather files. For example the energy consumption for refurbishment 22 calculated with the weather file from Meteonorm is 56 kWh/m^2 instead of the aforementioned 67 kWh/m^2. An even higher difference can be noticed for refurbishment 20, where the energy usage projected by the MN weather file is 103 kWh/m^2, while the one projected by the E+ weather file referring to CITY2 (Caselle) is 136 kWh/m^2.

In the analysis, referring to the work of Gaterell et al. Gaterell and McEvoy 2005 it is also important to include weather files referring to future years. Figure 5.3 points out the energy usage values of cooling and heating referring to the same city (Turin), source (E+), scenario (A2) and to present and future years. In this figure it is visible that not all the refurbishment cases behave in the same way when simulated with the four weather files. In particular, refurbishment 22 seems to have an opposite behaviour in terms of energy usage compared to the other cases. This is due to the fact that it is the only measure dealing with infiltration, while the others refer to the building envelope thermal properties. Some more analyses will be conducted in the following sections for refurbishment case 22. The results referring to the present weather file and the ones referring to the future weather file in 2080, are almost the same in all the cases. This could be an anomaly in the weather file generated with the software *CC WorldWeatherGen Climate change world weather file generator* due to the fact that it projects a global warming until 2050 and then an opposite trend in the 2080's.

As we already described in the previous chapters, climate change is affected by many uncertainties and so are the weather files that describe it. The evaluation of different refurbishment solutions based on energy usage calculated with those weather files cannot be conducted with just one weather file. There is the need to use more weather files referring to different years, scenarios and sources. The use of different weather files is unlikely to affect the ranking of the refurbishments solutions, at least for the majority of the cases. Anyway, the use of more weather files leads to the calculation of the range of possible variation in energy usage and helps to determine the robustness of various refurbishment solutions, as explained in the previous chapter.

The following paragraphs show the result of the assessment methodology for the case of Turin (45° latitude).

5.2 Robustness Evaluation

The robustness evaluation begins with the visualization of all the energy usage of each case in three box-whiskers plots, one for heating, one for cooling and one for the sum of them.

Figure 5.4 illustrates the annual energy usage for heating. The results highlight the sensitivity of different refurbishment measures to alternative climate scenarios. All the cases have two outliers. The use of PCM (RC21) is the only case in which there is a lower and an upper outlier, whereas for all the other solutions the two outliers are higher than the upper whisker. Almost all the medians are not in the middle of the boxes but are slightly toward the upper part. This means that the boxes are skewed towards larger volumes, i.e. the data set is not symmetrical around the mean and there are more values in the upper quartiles. The results which have similar values are generated with the MN

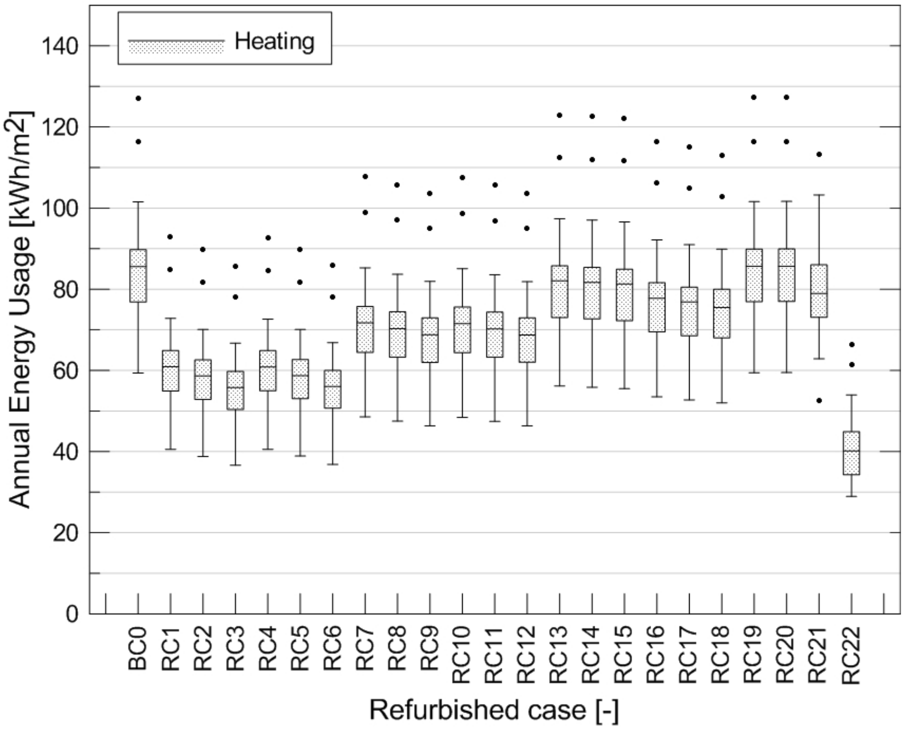


Figure 5.4: Annual final energy usage for heating at 45° of latitude.

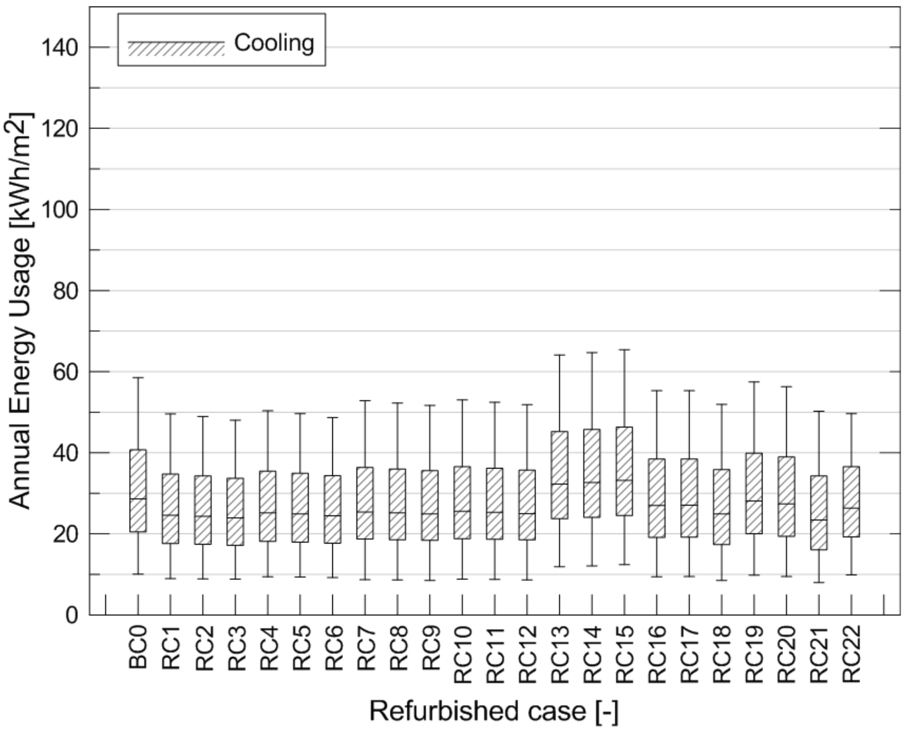


Figure 5.5: Annual final energy usage for cooling at 45° of latitude.

files, referred to different scenarios. As seen in chapter four, the energy usage due to different scenarios are quite similar. In general, almost all kind of refurbishment lead to a lower energy usage. Only the installation of shading systems both inside and outside the openings (RC19 and RC20 respectively) does not improve the energy performance of the building in terms of energy usage for heating. In terms of the height (spread) of the boxes and the length of the whiskers, the reduction of infiltration (RC22) seems to be the least sensitive refurbishment under future scenarios. On the other hand, both internal and external insulation of the walls (RC1, RC2, RC3 and RC4, RC5, RC6) seem to have the same smaller box height, but the difference between them is too small to be comparable. It is therefore necessary to attempt to quantify this spread of data by means of an RI.

Figure 5.5 shows the annual energy usage for cooling. The first thing that can be noticed is that, at this latitude, the cooling final energy is lower compared to the heating one. The differences between different refurbishments is really small and it seems that almost all the solutions behave the same way, beside the insulation of the floor with different U-values (RC13, RC14 and RC15). In this case, in fact, the insulation of the ground floor prevents the natural cooling from the ground from entering the building. The increase of the airtightness (RC22) does not have the same beneficial effect in terms of energy usage compared to the heating case. In the cooling box-whiskers plot there are no outliers and for this reason the whiskers represent the maximum and the minimum of each set of data. No outliers means that the values are more closely distributed around the median, which in fact is more in the middle of the box for almost each case. Another conclusion related to this fact is that the uncertainty for cooling is higher compared with the one for heating.

It is therefore clear that there is no connection between the energy performance for cooling and the ones for heating. The rankings developed on the basis of the robustness for different refurbishment differ between heating and cooling. In the case of cooling, in fact, almost all the refurbishment solutions seem to not have an appreciable effect on cooling energy loads, and therefore have almost the same negative grade in the rank. Due to the fact that both changes are going to happen anyway, we should evaluate the refurbishment measures on the basis of the sum of heating and cooling energy usage.

Figure 5.6 shows the sum of energy usage for heating and cooling. In general, there is not a uniform response to climate change among the different refurbishments. Due to the fact that the heating loads are higher than the cooling loads, the sum of the two energy figures is more influenced by the energy for heating. Also in this case, the box-whiskers plots referring to wall insulation are very similar to each other and difficult to assess. The box of the RC22 is larger compared to the heating box due to the fact that there are no more outliers. The medians of all the cases are in the middle of their respective boxes. In terms of robustness, the use of PCM (RC21) seems to be the least sensitive to climate change due to the small size of the box. It is also the only solution

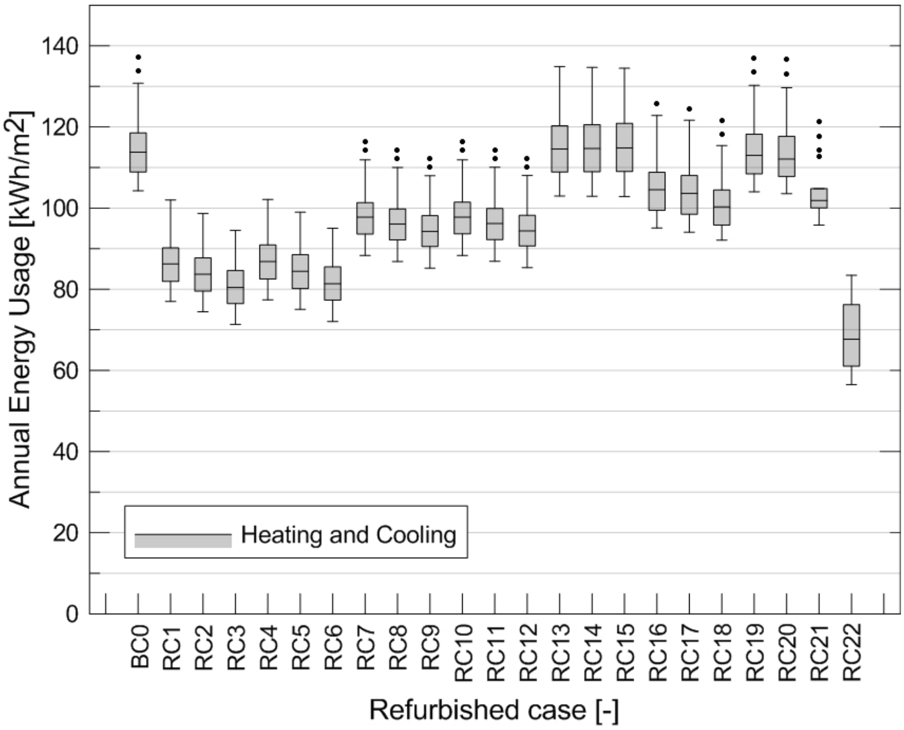


Figure 5.6: Annual final energy usage for heating and cooling at 45° of latitude.

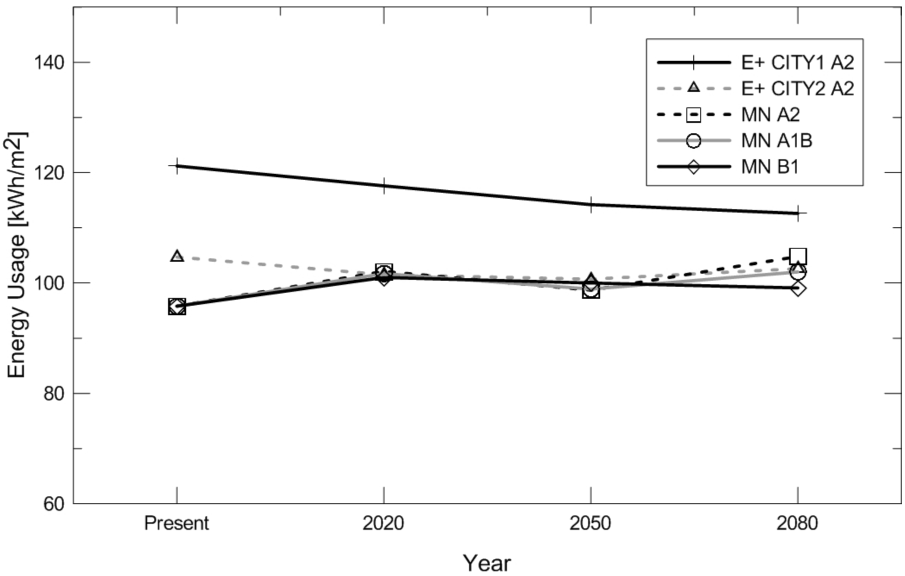


Figure 5.7: Annual energy usage for heating and cooling for RC21 in different years, sources, scenarios and cities.

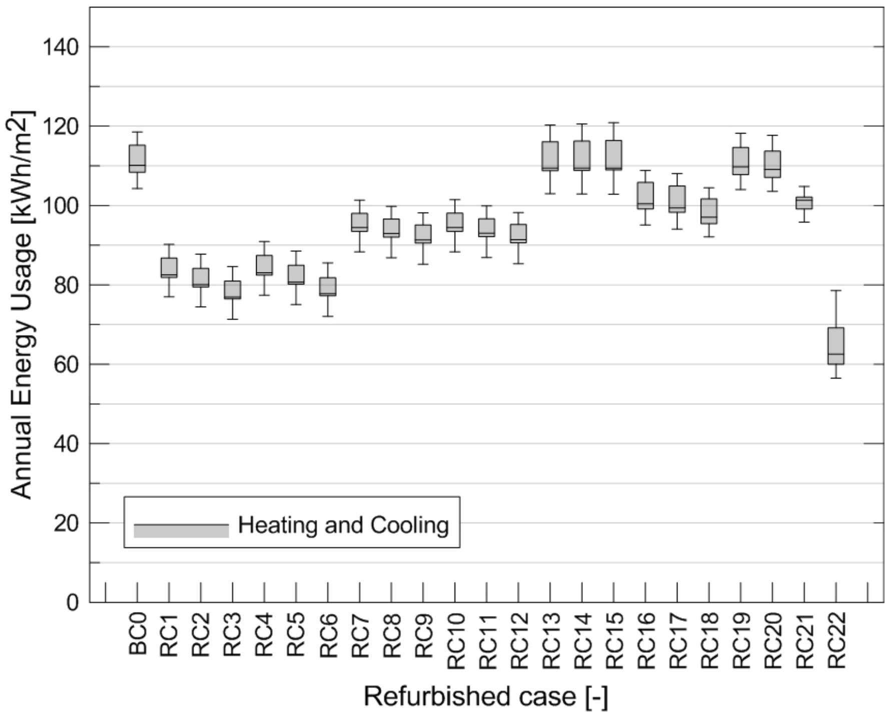


Figure 5.8: Annual final energy usage for heating and cooling at 45° of latitude with the elimination of the data coming from E+ CITY1 (Caselle).

which presents four outliers and with a very small, almost non-existent, upper whisker. Looking at the resultsmore closely, these four higher values refer to the weather file from the U.S. Department of Energy website referring to Caselle (E+ CITY1), in present and future years. Figure 5.7 shows the trends for the different sources, years and scenarios and highlights the anomaly in the E+ CITY1 results. Another anomaly that is seem in the same figure is the lower energy usage in the present for the MN weather files, i.e. the climate seems to become cooler in the 2020's for MN. This anomaly is likely caused by the input present weather data used to generate the future files. The input weather data for the 2020's climate is probably the one recorded between 1961 and 1990 instead of the new data set (2005-2009) which is used to generate the "present" weather file. This is why the future energy usage seems to be higher compared to the present, a result in contrast with the predicted global warming. Considering the elimination of the data set from E+ CITY1, the RC21 is the most robust to climate change.

Figure 5.8 displays the box-whiskers plots for all the refurbishments with the elimination of the results coming from E+ CITY1 (Caselle). RC21 is still the one with the smallest box, hence it is the most robust, but the other cases have substantially reduced dispersion of data as well. There are no more outliers and the whiskers represent the maximum and the minimum of the data set. In particular the lower whisker refers to the present weather file of MN and the upper one to the present weather file of E+

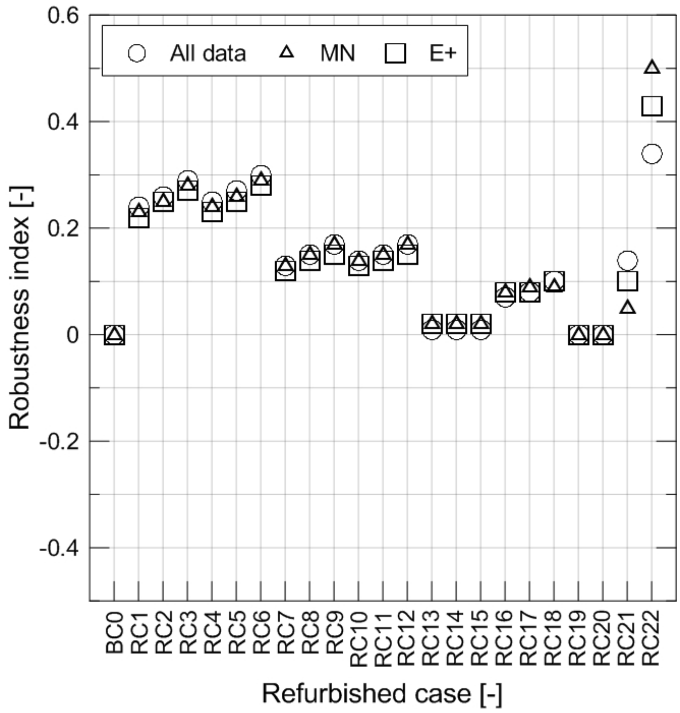


Figure 5.9: Refurbishment Index for heating at 45° of latitude. Comparison between the whole set of data, the MN data and the E+ data.

CITY2 (Turin). There is almost no difference between the widths of the boxes referring to the insulation of the wall and the roof (from RC1 to RC12).

At this point, to assess these differences, it is necessary to evaluate each refurbishment solutions with the Refurbishment Index (RI) introduced in the previous chapter.

As explained in the chapter before, the RI is not related to the magnitude of the energy usage but only to the dispersion of the data around a certain value. According to this index, in fact, a refurbishment that consume more energy but in a consistent way over time and for different sources, has a better rank compared to another refurbishment that consumes less energy but that is more sensitive to climate change.

Figure 5.9 illustrates the Refurbishment Index for heating. The three different symbols indicates the E+ data, the MN data and the whole set of data. This comparison is done due to the fact that we proved that the main difference between the results is due to the use of different sources, in our analysis Meteonorm and the U.S. Department of Energy website. Almost all the indices for each case have the same value, except for RC21 and RC22. For the first one, the RI is higher (hence, better) considering the whole set of data, while for the second one the MN data indicates a higher RI. According to the RI (referring only to the energy usage for heating) the best refurbishment in terms of robustness to climate change is RC22, the improvement of the airtightness of the building. In all the three cases it presents RI values higher than the other ones. The

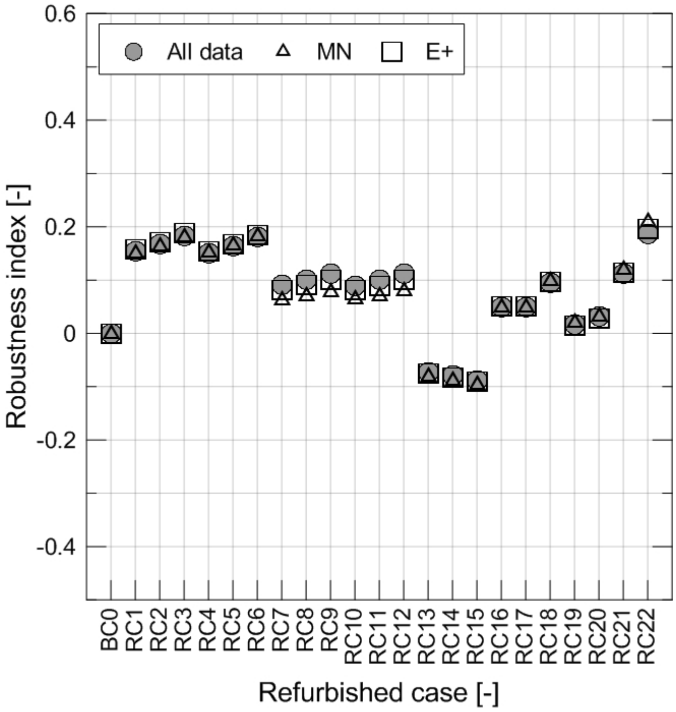


Figure 5.10: Refurbishment Index for cooling at 45° of latitude. Comparison between the whole set of data, the MN data and the E+ data.

improvement of airtightness, in fact, is an important measure during the cold season because it prevents uncontrolled loss of warmed air from a building.

Figure 5.10 shows the same comparison referring to the cooling energy usage. In this case the RI values are lower compared to the heating RI because they refer to the cooling box-whiskers plot, in which almost all the boxes had the same dimensions. The difference for the cooling Refurbishment Indices is that they have almost the same value independent of the source from where they come. In general, by using all the set of data, the RIs for the cases from RC7 to RC12 are higher, whereas for the other cases is lower or the same. Also for the cooling the least scattered set of data –hence the higher RI– refers to RC22, the decrease of infiltration. Its RI value is close to the ones of the internal and external wall insulation referring to the PassiveHouse standard (RC3 and RC6 respectively). It is interesting to note that the ranking of the different refurbishment solutions in terms of robustness to climate change is the same for both cooling and heating.

Figure 5.11 compares the RIs for cooling and heating (indicated in figures 5.9 and 5.10 with the same symbols) and their sum. All the eighteen values for each refurbishment are taken into account, without making any distinction between the results calculated with MN weather files and E+ weather files due to the fact that the difference was small for both heating and cooling in the majority of the refurbishments. The figure

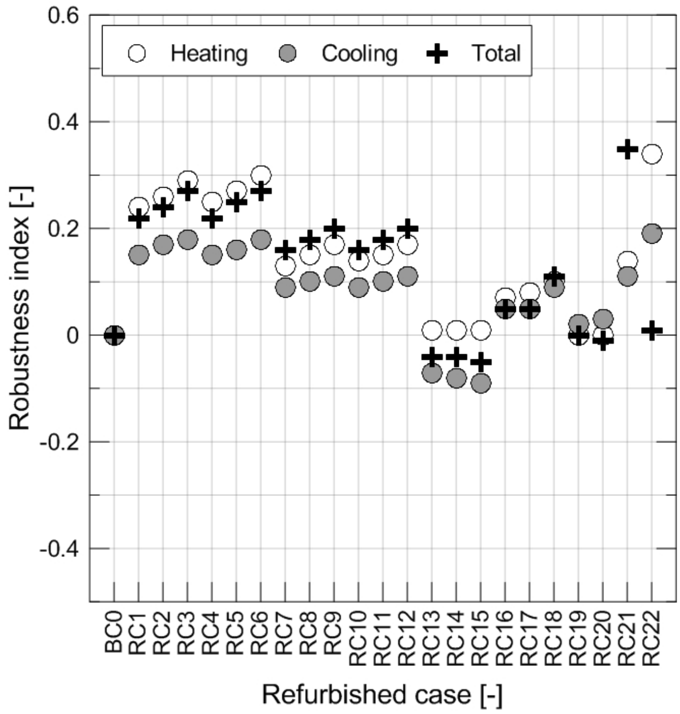


Figure 5.11: Refurbishment Index for cooling, heating and the total energy usage at 45° of latitude, considering all the data.

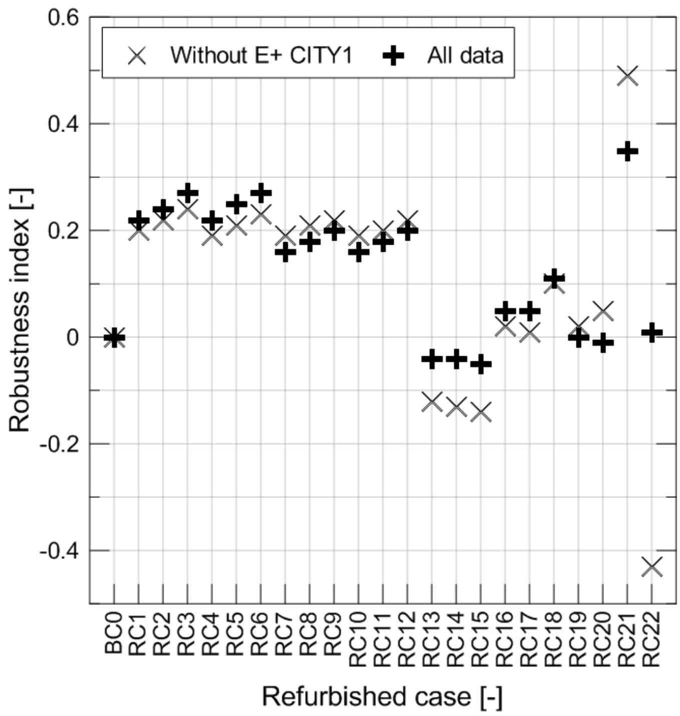


Figure 5.12: Refurbishment Index for the total energy usage at 45° of latitude. Comparison between the all set of data and the reduced set.

shows clearly that in the majority of cases the RIs for heating are higher than the ones for cooling, except for the shading system refurbishments. In these cases, in fact, the energy usage is more influenced in the hot season than in the winter one, due to solar gains through the windows.

Figure 5.12 shows the difference in the RI between the use of all the data and the use of the data without E+ CITY1 values, which we demonstrated to be different from the other weather files in terms of energy usage. As seen in the box-whiskers plots referring to the two cases (cf. figures 5.6 and 5.8), the refurbishment cases behave in different ways. The most relevant variation of the RI concerns RC22, which considering all the data is almost zero and deleting the E+ CITY1 values is the lowest one. Referring to both cases, the use of PCM (RC21) is the least sensitive refurbishment under many climate change scenarios. The increase of airtightness is the least robust refurbishment considering the reduced set of data, while referring to the total energy figure, RC15 (insulation of the floor) is the worst refurbishment. Their negative values mean that their ranges are larger than the range of the base case, i.e., they have a bigger dispersion of data. This does not necessarily mean that they consume more energy. By looking ate the box-whiskers plot (cf. figures 5.6 and 5.8), in fact, their results overlap almost completely with the base case, with same results being lower. It is only their ranges that are bigger than the base case and therefore their RIs are negative. Regarding the other refurbishments, case 19 and 20 (shading systems) are comparable to the base case, and each case of the thermal envelope properties improvement referring to the PassiveHouse shows a higher RI compared to the other results. The most robust solution between external and internal wall insulation is the external one if the reduced set of data is taken into account. In any case, their difference is very small, almost irrelevant. In the ranking according to the RI the wall insulation interventions are followed by the insulation of the roof and the use of triple glazing with coating.

5.3 Energy Saving Evaluation

The energy saving evaluation begins with the visualization of the difference between refurbished cases (present and future values) and the base case (present value) in terms of energy usage, i.e. the comparison C which includes A and B. Three floating bar charts are used to illustrate the results for heating, cooling and the sum of the two energies.

Figure 5.13 shows the energy difference ranges for heating energy usage between the base case (present) and the refurbishment case (present, future). Comparison C includes comparison B (base case present at current days and base case in the future) and the results are shown in the first four floating bars of the figure. The first bar is equal to zero because it refers to the comparison of the base case at present with itself. In the case of heating there is always a positive difference between the energy usage

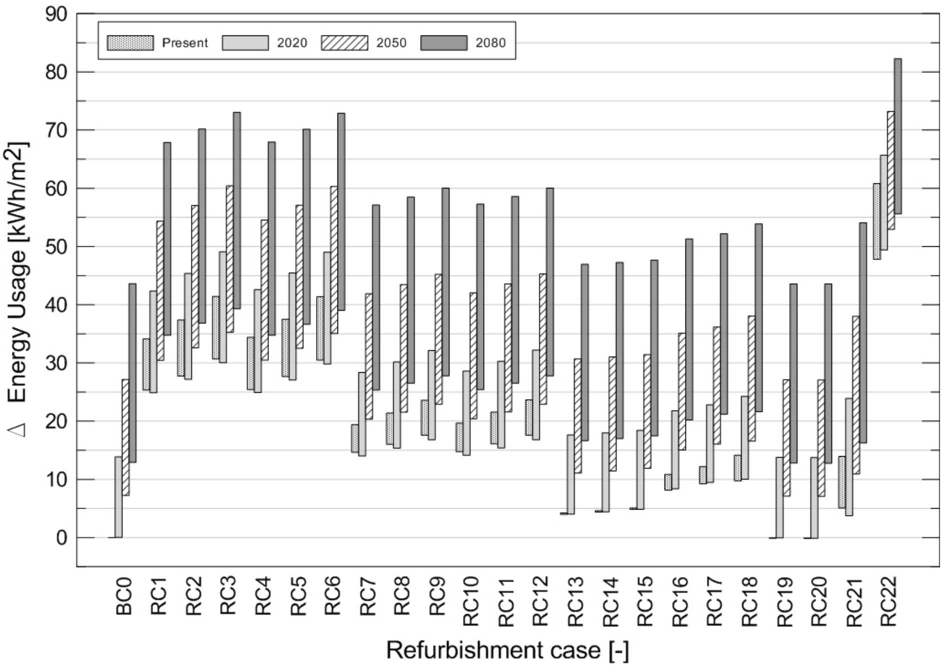


Figure 5.13: Energy difference ranges for heating between base case and refurbishment cases in different years.

of the base case and the ones of the refurbishment, hence there is always an energy saving. The only exception is for the shading systems refurbishments (RC19 and RC20), where the energy saving is almost zero as well. Figure 5.13 illustrates that the ranges of energy saving are different in the four years. In particular, the further a time snap is from the present, the more uncertain is the climate prediction, which in turn implies a wider range of energy saving possibilities. For this reason the present ranges are smaller than the rages for 2020, 2050 and 2080. The bigger energy saving in 2080s is also due to general warming. The bars indicate the maximum and the minimum for all years of the set of data we have. If the weather files are considered as probable future scenarios, then they must be considered together and not singularly. We have, therefore to compare the ranges of energy variation. By looking at the ranges, the majority of the refurbishments overlap with each other. Only the improvement of the airtightness (RC22) presents very high energy savings in all the years, but it is also the only one which has a wide range for the energy saving at present. Also the base case will save some energy in the future, but only due to climate change.

Figure 5.14 illustrates the differences between energy usage for the base case at present and the refurbishment cases, in different years. In this case the ranges are mostly negative (beside for the present) due to the fact that the climate is going to be warmer and therefore the energy usage for cooling is going to be higher compared to today. It is interesting to notice that, according to the assessment methodology that takes into

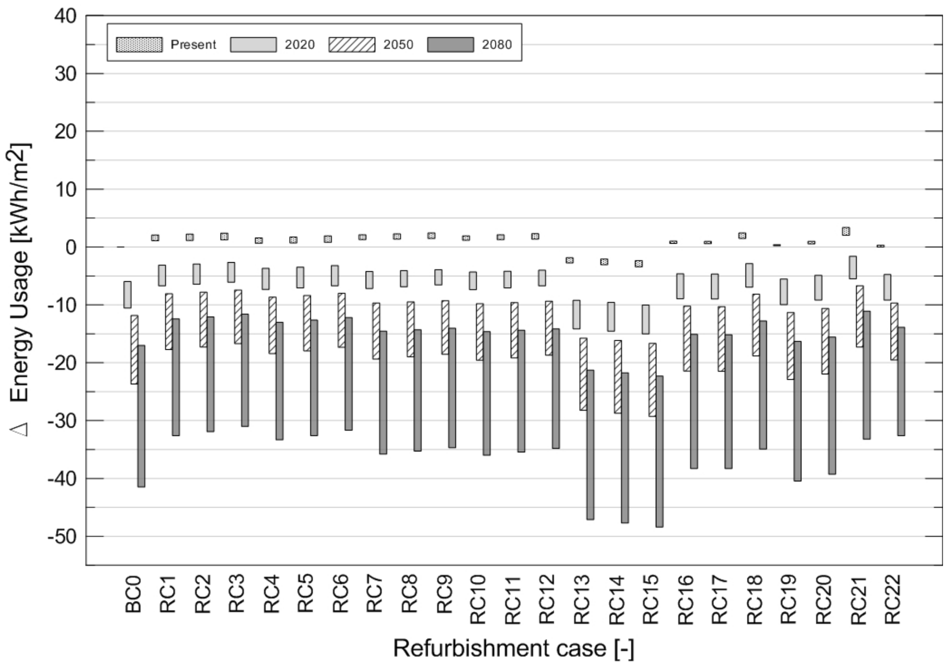


Figure 5.14: Energy difference ranges for cooling between base case and refurbishment cases in different years.

account only current weather files, it is possible to make some design decisions related to the energy usage. For example, referring to the present ranges, the use of PCM is the refurbishment measure which saves more energy compared to the others. By taking into account the future years, it can be said that the same measure will consume more energy compared to the base case today. Its ranges are similar to the others or even worse. Figure 5.14 demonstrates that none of the refurbishment solutions is good in future climates, because they will consume more energy in any case. The insulation of the floor (RC13, RC14, RC15), for example, leads to even higher energy usage in 2080 compared to the base case in 2080.

It is necessary to see how different refurbishments behave in terms of total energy usage. Comparison C between base case and refurbishment is shown in figure 5.15. The total energy usage is more influenced by the heating energy usage, as demonstrated in the box-whiskers plots. The ranges referring to the present are almost the same as those for heating, while the ranges referring to 2080 are much smaller compared to the heating ranges. In conclusion, the present ranges are the ones which have more variations through the different refurbishment. The difference between the other ranges is difficult to see, especially in the same refurbishment group such as wall insulation, floor insulation or substitution of the windows. The use of PCM is the only refurbishment which presents a wider variation in 2020, but the other ranges are comparable to the wall insulation cases (RC1/RC6). As we did for the box-whiskers plot data, we want

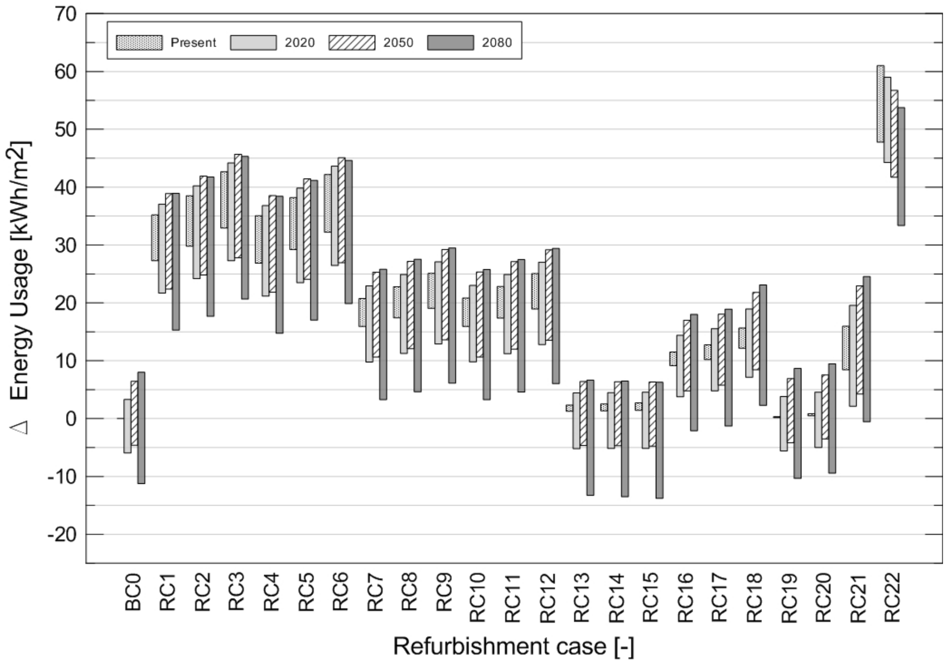


Figure 5.15: Energy difference ranges for heating and cooling between base case and refurbishment cases in different years.

to eliminate the E+ CITY1 set of data (referring to Caselle) to see if there are big differences in the evaluation of the refurbishments.

Figure 5.16 shows that the ranges of all the years are substantially reduced compared to the ranges for the whole set of data. This is due to the fact that the ranges indicate only the minimum and the maximum. In our case the maximum was always associated with the E+ CITY1 weather files referring to Caselle. Deleting these four data points (one for each year), all the maximum values are lower and the ranges are smaller. However, the ranking of each refurbishment measure does not change. The increase of insulation (RC22) is still the best measure in both present and future years. It is a good solution due to the high energy saving and to the small ranges.

At this point of the analysis it is necessary to use the Energy Saving Index to assess the refurbishments more reasonably. Figure 5.17 illustrates the Energy Saving Index for heating. The three different symbols indicates the E+ data, the MN data and the whole set of data. This comparison is done due to the fact that we proved earlier that the main difference between the results is due to the use of different sources, in our analysis Meteonorm and the U.S. Department of Energy website. Almost all the indices for each case have the same value, besides the RC21 and RC22. For the first one, the ESI is higher (hence, better) considering the E+ data, while for the second one the MN data indicates an higher ESI. According to the ESI referring to heating the best refurbishment in terms of energy saving in comparison with the base case is RC22, the

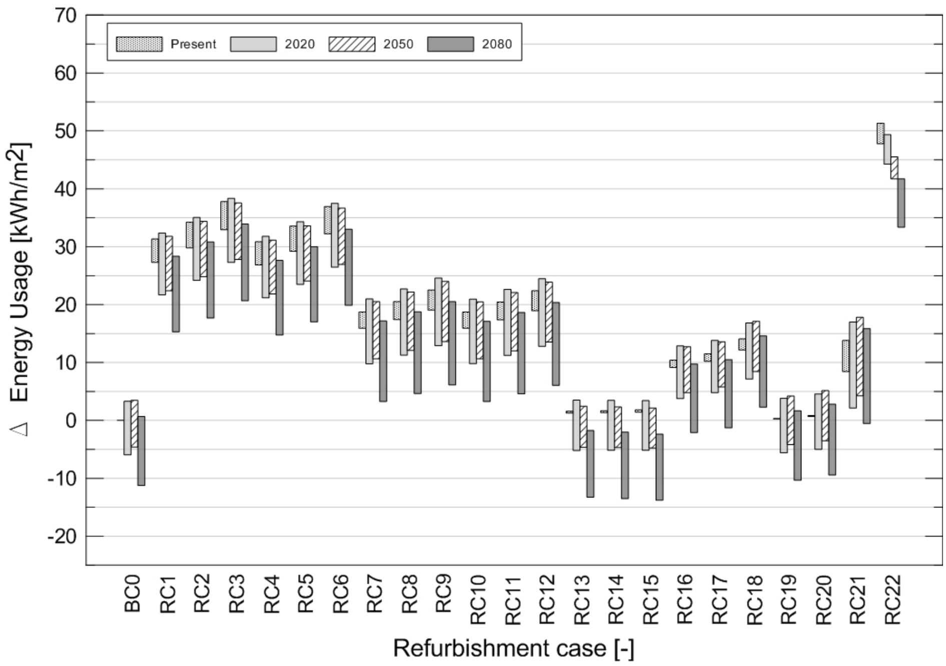


Figure 5.16: Energy difference ranges for heating and cooling between base case and refurbishment cases in different years, considering a reduced set of data (without E+ CITY1).

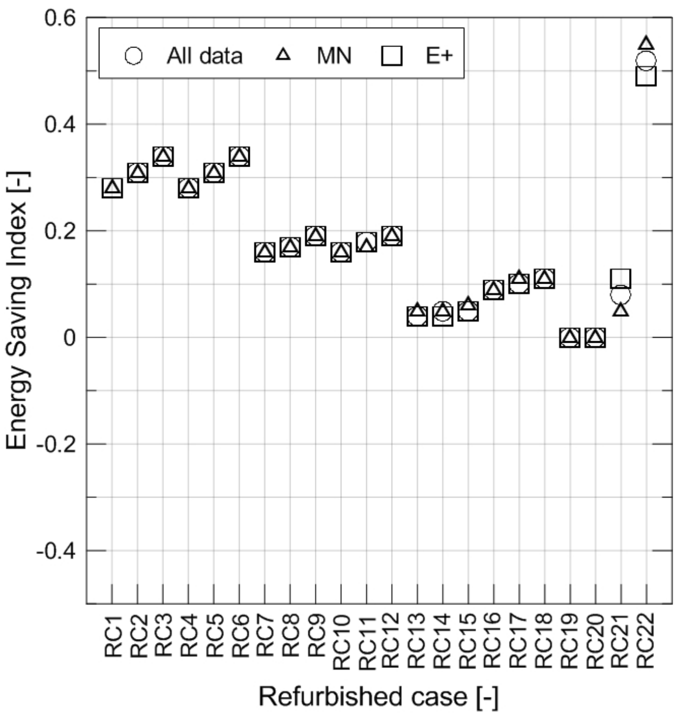


Figure 5.17: Energy Saving Index for heating. Comparison between two sources and the whole set of data.

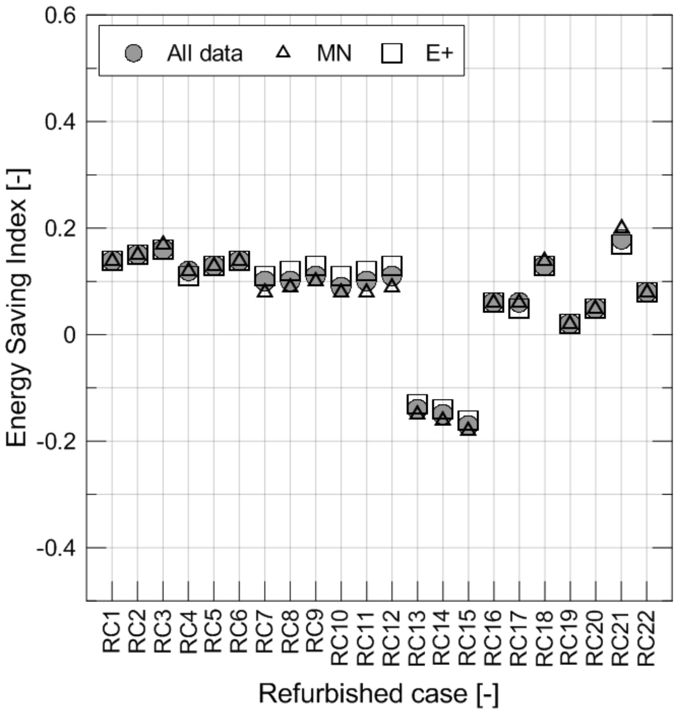


Figure 5.18: Energy Saving Index for cooling. Comparison between two sources and the whole set of data.

improvement of the airtightness of the building. In all three values, referring to the data coming from different sources and to all the set of data, it presents ESI values higher than the other ones. It is clearly visible that the results are grouped according to a particular set of refurbishment measures (e.g., wall insulation, floor insulation, shading systems). The ESI is calculated only for the refurbishment interventions and not for the base case since it is calculated using a difference from the base case.

Figure 5.18 shows the same comparison referring to the cooling energy difference between base case and refurbishment. In this case the ESI values are lower compared to the ESI for heating because they refer to the cooling energy usage values, which are lower compared to the heating ones. The difference in the cooling ESIs is that they have almost the same value independent of the source from where they come, especially for the cases from RC1 to RC6, RC19, RC20 and RC22. In any case, it is interesting to note that the ranking of the different refurbishment solutions in terms of energy saving is not the same for cooling and heating.

Figure 5.19 compares the Energy Saving Index for heating, cooling and their sum using all the eighteen data for each refurbishment. The symbols for the cooling and the heating are the same as figures 5.17 and 5.18, whereas the total ESI is shown with a cross. This last value indicates a number in between the heating ESI and the cooling ESI, always closer to, and therefore more influenced by, the heating ESI. Also in this

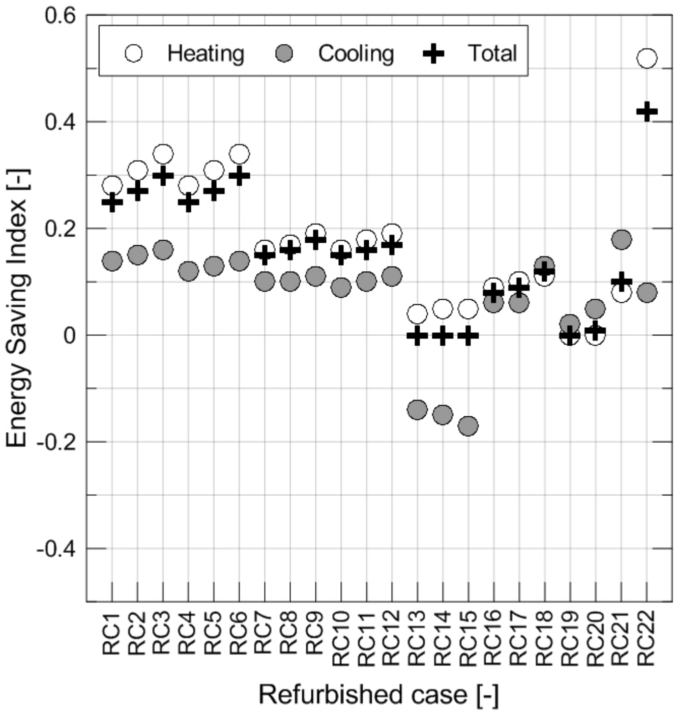


Figure 5.19: Energy Saving Index for heating and cooling and the sum of them using all the data.

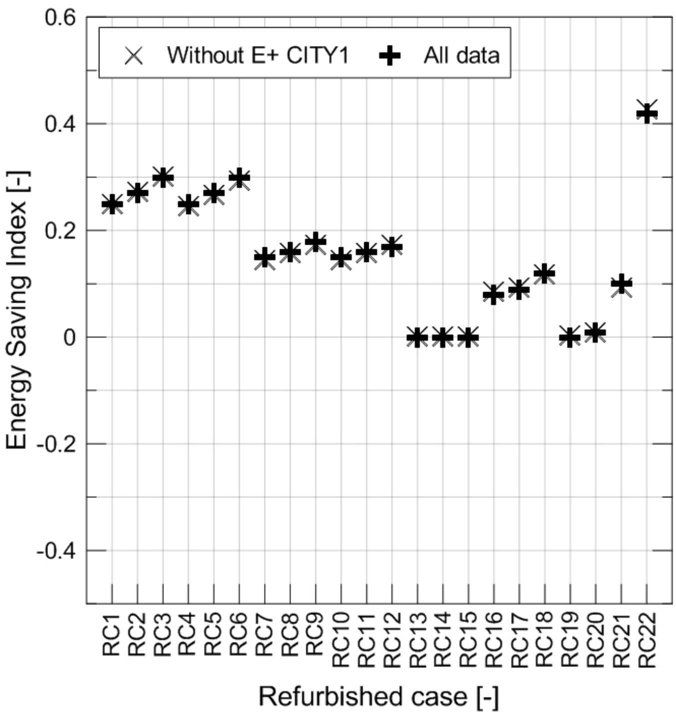


Figure 5.20: Energy Saving Index for heating and cooling and the sum of them without E+ CITY1 (Caselle) data.

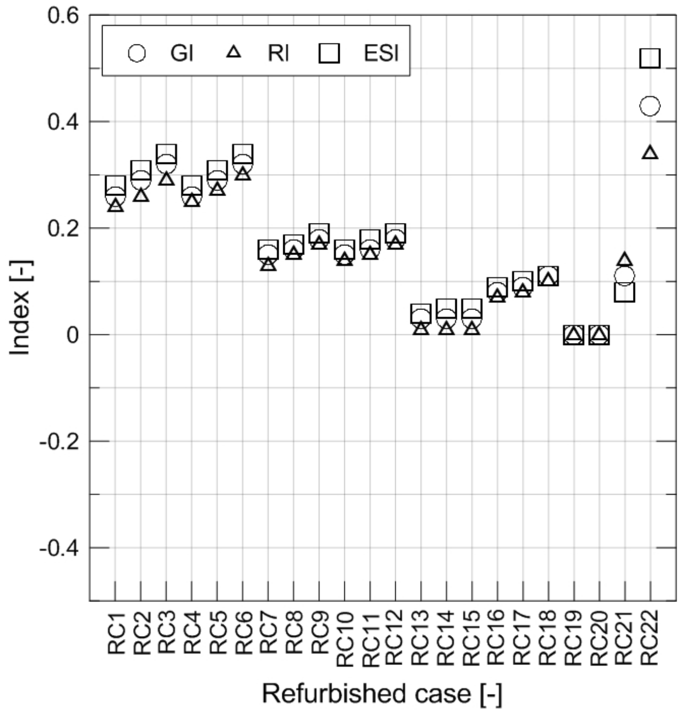


Figure 5.21: Gather Index for heating. Comparison between two sources and the whole set of data.

case the ranking of the different refurbishment solutions does not change. The increase of the airtightness (RC22) is the best energy saving measures, while the insulation of the floor (RC13, RC14, RC15) and the use of shading systems (RC19, RC20) are the worst ones.

As for the Refurbishment Index and for the floating bar chart, we want to show the results of the total ESI using the reduced set of data, without the E+ CITY1 results that we demonstrated to be the most different between all the others. Figure 5.20 shows that the difference between the two indices is irrelevant and sometimes zero. The final ranking is still the same.

5.4 Overall Evaluation

The overall evaluation with the Gather Index (GI) is made with the combination of the two indices related to the robustness (RI) and to the energy saving (ESI) for each refurbishment case. In the calculation of the GI we decided to give the same weight to the two indices. In this way, the GI is the average between the RI and the ESI.

Figure 5.21 shows the GIs for the heating, comparing the data with the RI and the ESI for heating. Due to the fact that the RI and the ESI for heating are almost the same for all the cases, the GI reproduce the same trend for all the refurbishments. The

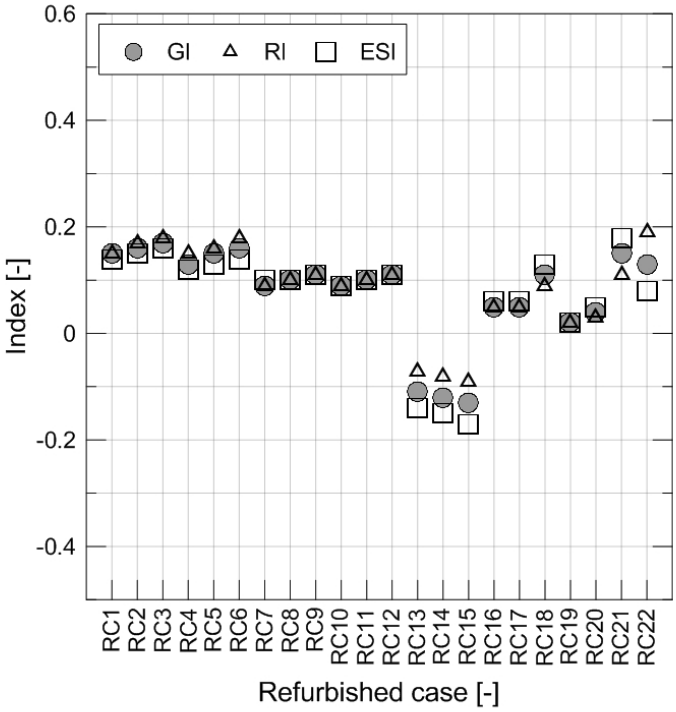


Figure 5.22: Gather Index for cooling. Comparison between two sources and the whole set of data.

figure indicates that the GI is exactly in between the two values of the other two indices because it is the average of the two numbers. The bigger difference between RI and ESI, and therefore GI, is in the last two solutions (RC21 and RC22). The increase of the airtightness (RC22) is the best solution considering all the three indices, even if it is only a better refurbishment in terms of energy saving instead of robustness. For the other refurbishments the ranking is the same using the three indices. Following the increase of airtightness, the external and internal insulation of the walls (RC1/RC6) is the second best solution. The results between internal and external insulation are comparable. Then we find the external and internal insulation of the roof, the use of PCM, The substitution of the windows and the insulation of the floors. The use of shading systems is useless in terms of both robustness and energy saving for heating.

Figure 5.22 illustrates the comparison between GI, RI and ESI for the cooling energy saving. In this case as well the three indices have almost the same values, besides RC13, RC14, RC15, RC21 and RC22. In the case of the floor insulation (RC13, RC14 and RC15), the values are all negative but they are worse for the ESI than for the RI. The use of PCM has a higher index in terms of energy saving and a lower one in terms of robustness. It is the opposite for the improvement of the airtightness of the building. According to the GI for cooling, the best refurbishment is the use of external wall insulation, followed by the use of internal insulation and the use of PCM. The difference

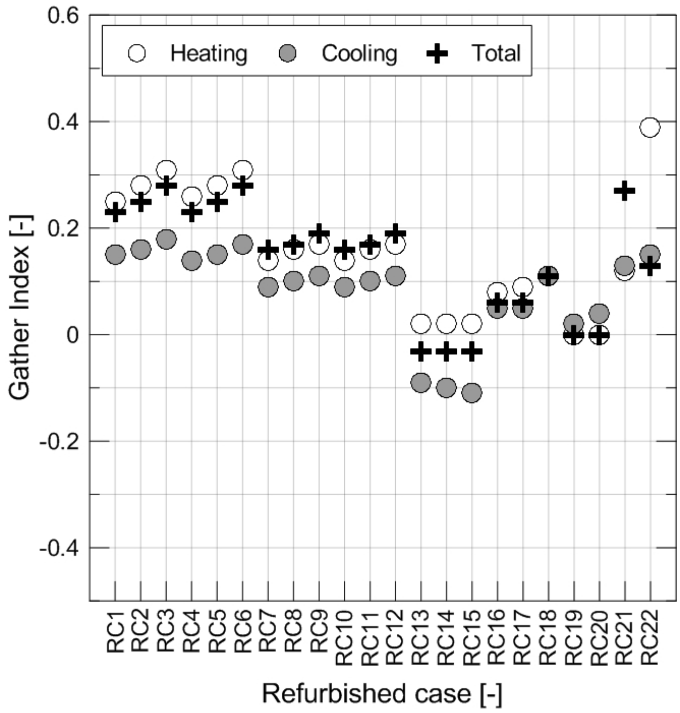


Figure 5.23: Gather Index for heating, cooling and the sum of them using all the data.

between these refurbishments is almost irrelevant.

Figure 5.23 shows the comparison between the Gather Index for heating, cooling and their sum using all the data for each refurbishment. The total GI is closer to the heating GI, besides the last two refurbishments (RC21 and RC22). According to the total GI, the final ranking of the refurbishment solutions considering both the robustness to climate change and the energy saving potential at a latitude of 45° is the following:

- RC3, RC6: external and internal wall insulation according to the PassiveHouse standard (U-value equals to 0.15 $\frac{W}{m^2K}$)
- RC2, RC5: external and internal wall insulation according to the second level of the Italian standard (U-value equals to 0.25 $\frac{W}{m^2K}$)
- RC1, RC4: external and internal wall insulation according to the first level of the Italian standard (U-value equals to 0.33 $\frac{W}{m^2K}$)
- RC21: use of PCM
- RC22: increase of the airtightness of the building
- RC9, RC12: external and internal roof insulation according to the PassiveHouse standard (U-value equals to 0.15 $\frac{W}{m^2K}$)

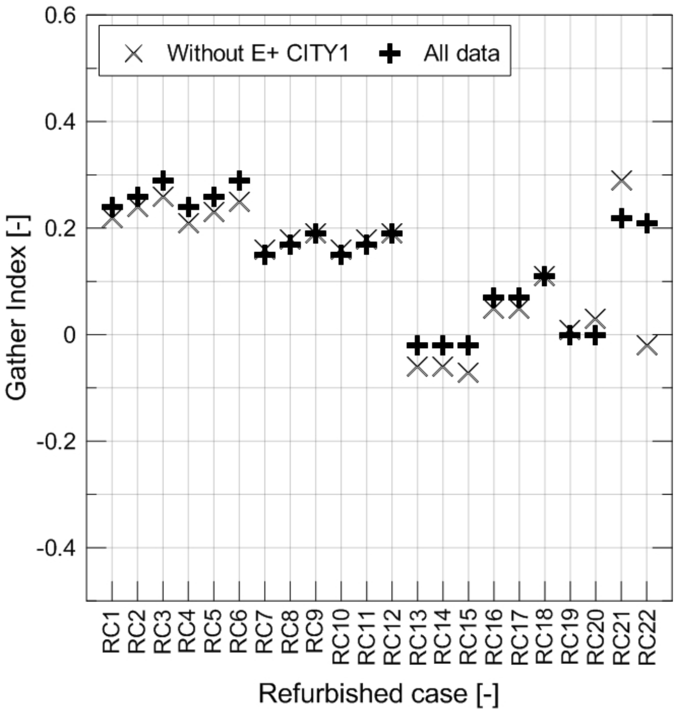


Figure 5.24: Gather Index for heating and cooling. Comparison between all the data and the set of data without E+ CITY1 results.

- RC8, RC11: external and internal roof insulation according to the second level of the Italian standard (U-value equals to 0.23 $\frac{W}{m^2K}$)
- RC7, RC10: external and internal roof insulation according to the first level of the Italian standard (U-value equals to 0.30 $\frac{W}{m^2K}$)
- RC18: use of triple glazing with argon
- RC16, RC17: use of double and triple glazing
- RC19, RC20: use of shading systems
- RC13, RC14, RC15: insulation of the floor

It is clear that the group of similar refurbishments behave in the same way, denoting a "grouping behaviour". In particular there is no difference between the internal and external insulation for both walls and roof.

Figure 5.24 shows the comparison between the total GI considering the whole set of data and the one without E+ CITY1. The ranking is the same as mentioned before for all the refurbishment solutions besides the use of PCM (RC21) and the increase of airtightness (RC22). Without considering the weather files referring to Caselle the use of PCM becomes the best refurbishment for both robustness and energy saving

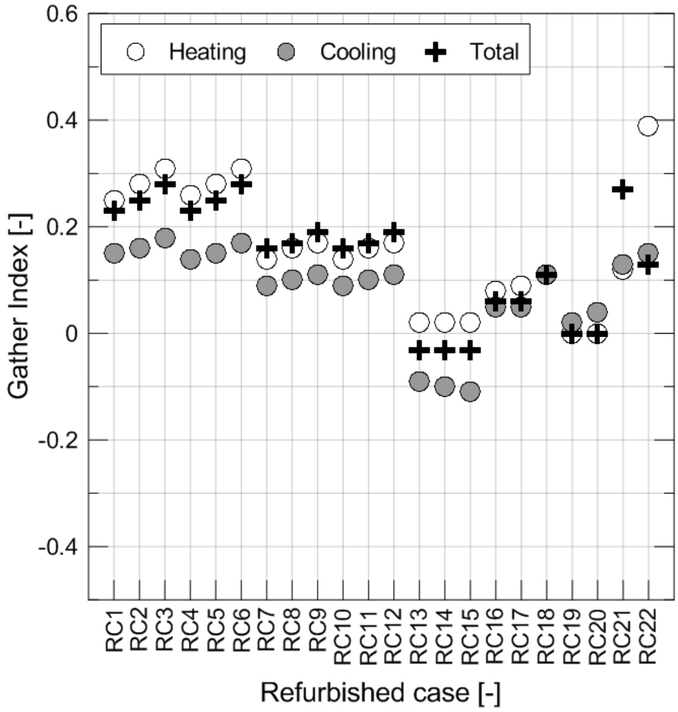


Figure 5.25: Gather Index for heating, cooling and the sum of them using all the data and a different weights for the two indices.

potential. On the other hand, the increase of the airtightness turns out to be one of the worst refurbishments, just better than the floor insulation.

Figure 5.25 illustrates the GI for heating, cooling and their sum using different weights for the two indices. As an example, we decided to give more importance to the robustness by assigning a weight of 0.7 to the RI and a weight of 0.3 to the ESI. The figure shows that the ranking is the same as using equal weights, except for the use of PCM and the increase of the airtightness. In this case, in fact, the use of PCM becomes the second best refurbishment after the internal and external insulation of the walls according to the PassiveHouse standard, whereas the increase of the airtightness solution turns out to be worst, except for the roof insulation group.

Figure 5.26 shows that, deleting the E+ CITY1 set of data, all the total GI seem to have a similar value around 0.1. The ranking tend not to vary, with a few exceptions.

As in the study of Tian and de Wilde (2011) we highlighted that the ranges of data –hence uncertainties– are due to both climate change projections and intervention in the building envelope. In comparison with their conclusion regarding the thermal performance of the Roland Levinsky Building at the authors' campus, we can state that:

- We agree that, due to climate warming, annual heating energy usage will decrease and annual cooling energy usage will increase.

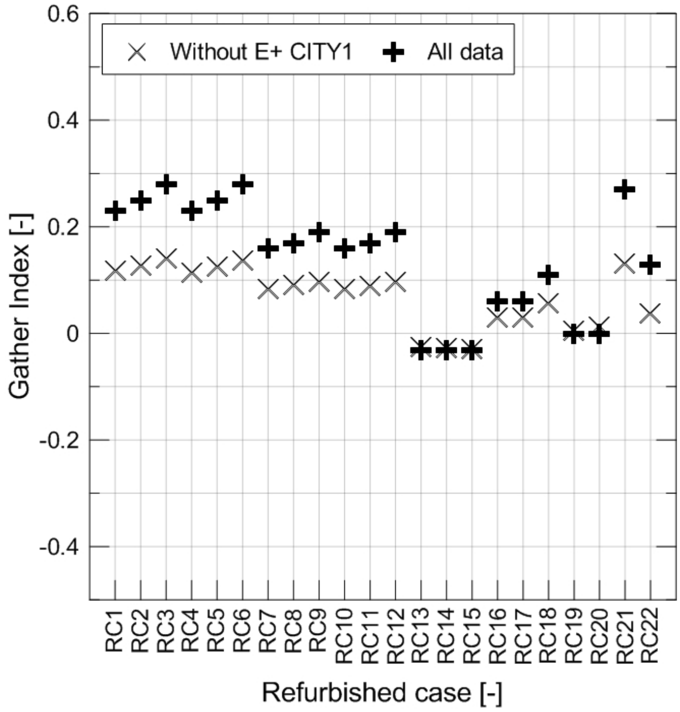


Figure 5.26: Gather Index for heating and cooling. Comparison between all the data and the set of data without E+ CITY1 with different weights for the two indices.

- We disagree upon the fact that the uncertainty in predicted annual cooling energy usage is significantly higher than the one for heating. There is a difference, but not remarkably high.
- We agree that the main variations due to climate change are related to temperature variation, while other weather variables (e.g. solar radiation) influence less the energy usage. This fact can be proved by the relatively small variations of thermal behaviour of the refurbishments related to the shading systems in comparison with the base case.
- We agree upon the fact that infiltration rate has important effects on heating energy. In our study, it is the less robust but it permits to save the highest amount of energy.

Chapter 6

Comparison Between Latitudes

Climate change is going to have different impacts in climate zones worldwide. In this study we focus on Europe and see how the increase in heat stress influences the built environment at different latitudes. For instance, in cold climates at high latitude, global warming is likely to lead to a reduction in heating energy usage. On the contrary, in southern European countries it will bring about an increase in energy consumption due to increased use of cooling systems. We want to analyse both the reduction in heating energy usage and the increase in cooling energy usage, and how this interaction varies at different latitudes throughout Europe.

As in the previous chapter, we will use graphs and indices to assess the refurbishments at different latitudes. Due to the fact that we saw “grouping behaviour” in the previous analysis, we decided to use only the best refurbishment for each group in terms of Gather Index. For this reason, the refurbishment solutions that we will analyse in different climatic zones are:

- RC3: external wall insulation, PassiveHouse standard (U = 0.15 $\frac{W}{m^2K}$)
- RC9: external roof insulation, PassiveHouse standard (U = 0.15 $\frac{W}{m^2K}$)
- RC15: insulation of the floor, PassiveHouse standard (U = 0.15 $\frac{W}{m^2K}$)
- RC18: triple glazed windows with argon
- RC20: external shading systems
- RC21: PCM
- RC22: increasing the airtightness of the building

For each refurbishment and the base case we will present the behaviour of the passive measures at different climatic zones in terms of total energy usage. Then we will illustrate the energy saving for the sum of heating and cooling in different years and for different places. The comparison is made between each refurbishment (in present and future years) and the base case at present. Finally, we will compare the RI, ESI and GI referring to the total energy usage in different climatic regions.

The questions that we want to address in this part of the study are:

- Is the latitude (and a relatively close longitude) a good representation of a climatic zone?
- How do refurbishment solutions behave in different climatic zones?
- Is there a refurbishment that is robust across climatic zones?

In the next section we will answer the first question, whereas the other two will be addressed in the analysis of the graphs and the indices.

6.1 Latitudes, Longitudes and Climatic Zones

In the analysis of the case study for Turin we highlighted the fact that the results coming from E+ CITY1 referring to Caselle were the most different compared to the others. This fact is probably due to the years of the two records, which are different (the data for Turin are from IWEC and the one for Caselle are from IGDG). Another factor could be the difference in latitude and longitude between the cities.

In the following part, we will show a graph for each latitude indicating the trend of the total energy usage of the base case in different years and according to the five groups of weather source and scenario (E+ CITY1, E+ CITY2, MN A2, MN A1B, MN B1). In particular, the E+ CITY1 refers to the "twin" city for each latitude of which we have weather data only coming from E+.

For the majority of the cases the total energy usage results coming from the "twin city" of E+ (E+ CITY1) are different from the other values. Figure 6.2, for example, shows a big difference between the data coming from Copenhagen (E+ CITY2 and MN) and the one coming from Oban (E+ CITY1). This is the only case in which the two cities are not at the same latitude but differ by 0.80°. Moreover the two cities are the furthest also in terms of longitude, with a difference of 18.14°.

Figures 6.4, 6.5 and 6.6, referring to Paris, Turin and Barcelona indicate a smaller difference between the E+ CITY1 set of data and the others in comparison with Copenhagen, but still relevant. Turin and Caselle are the two closest cities in terms of both latitude and longitude (a difference of 0° and 0.04° respectively). Barcelona and Porto are the second pair with a great distance in terms of longitude, with a difference of 10.75°, whereas they differ only 0.05° in latitude. Paris and Brest follow Copenhagen and Barcelona in terms of distance in longitude, with a difference of 6.28°. Also their difference of 0.28° in terms of latitude is quite relevant.

Figures 6.1, 6.3 and 6.7, referring to Stockholm, London and Athens respectively, show the smallest difference between the sets of data. Athens and Andravida are at

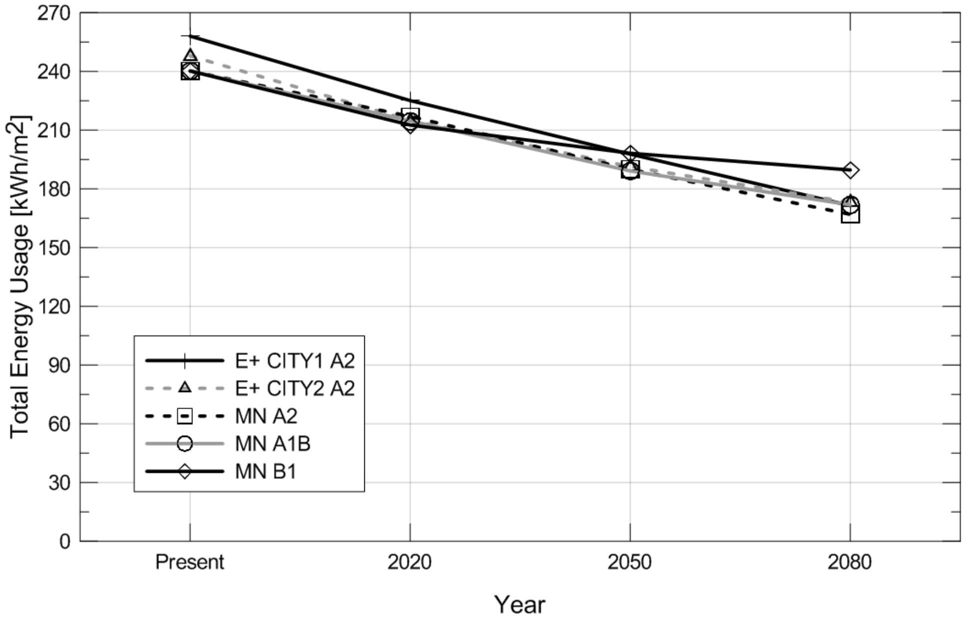


Figure 6.1: Stockholm: total energy usage calculated from different weather files.

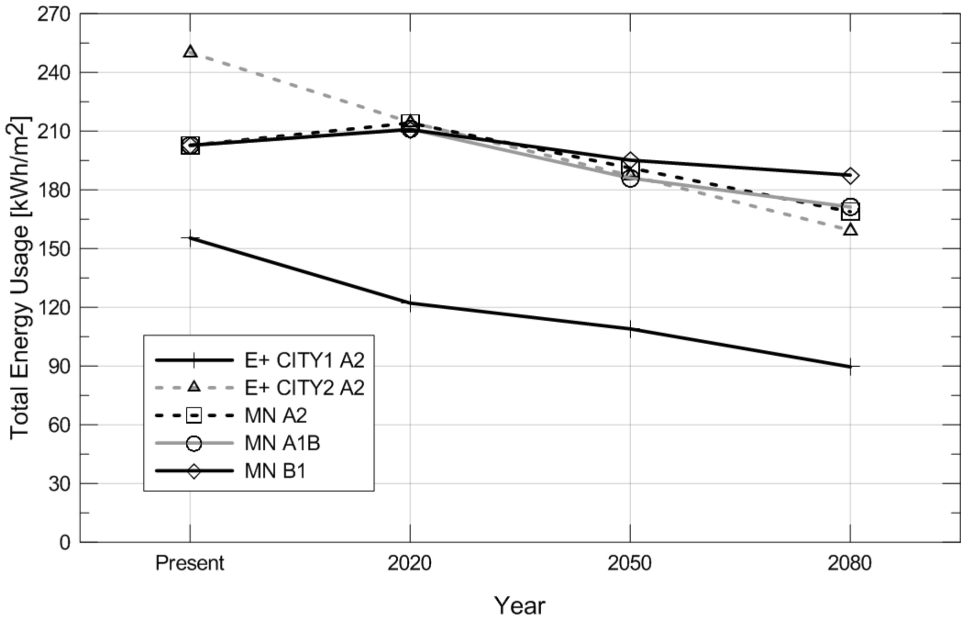


Figure 6.2: Copenhagen: total energy usage calculated from different weather files.

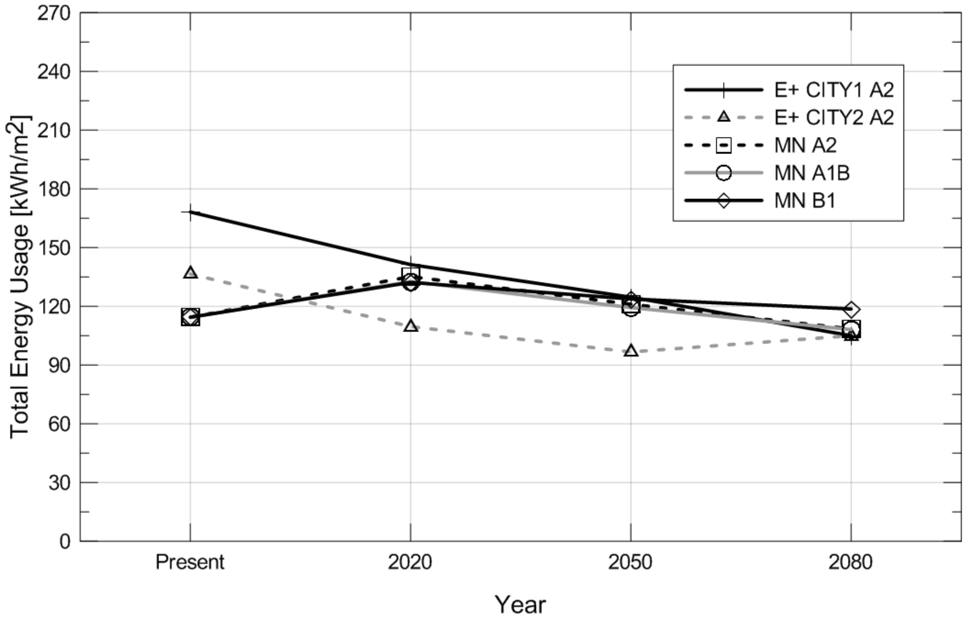


Figure 6.3: London: total energy usage calculated from different weather files.

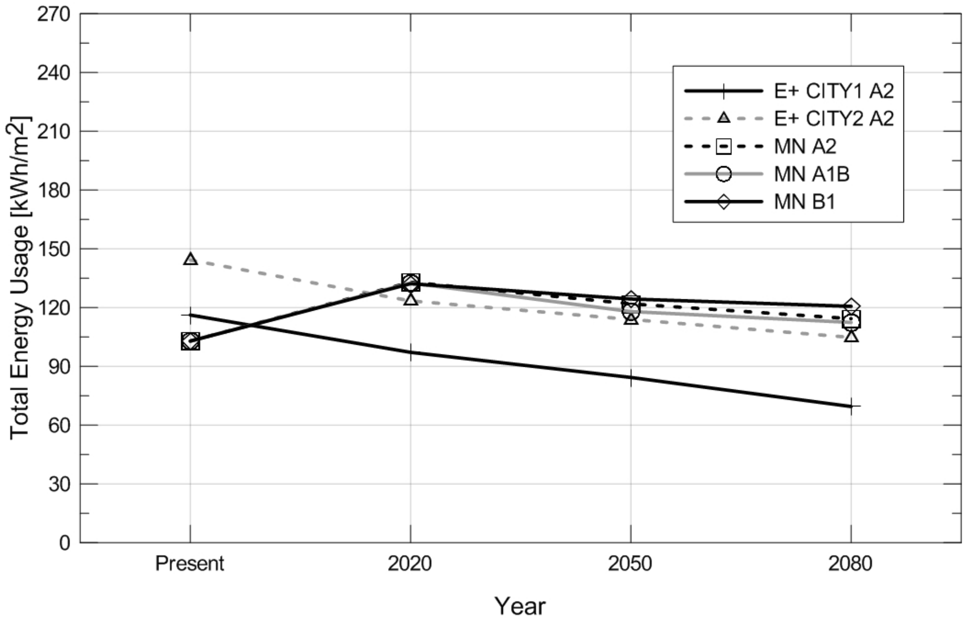


Figure 6.4: Paris: total energy usage calculated from different weather files.

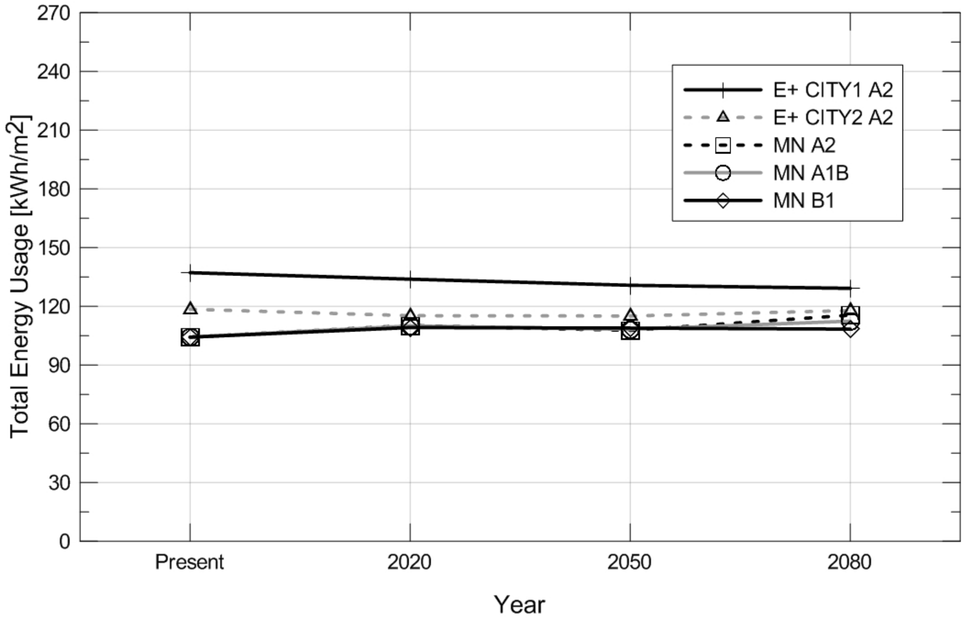


Figure 6.5: Turin: total energy usage calculated from different weather files.

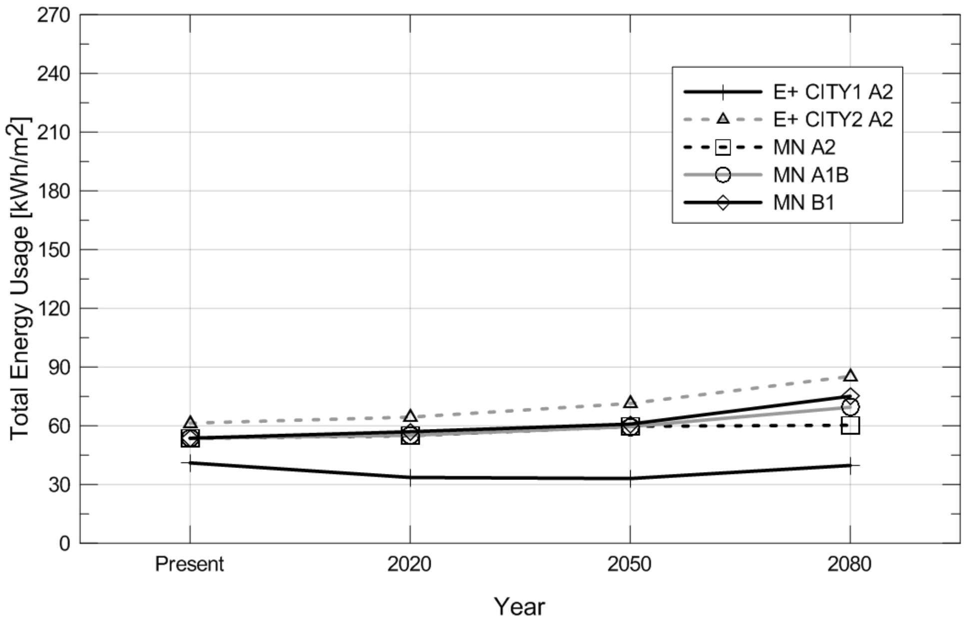


Figure 6.6: Barcelona: total energy usage calculated from different weather files.

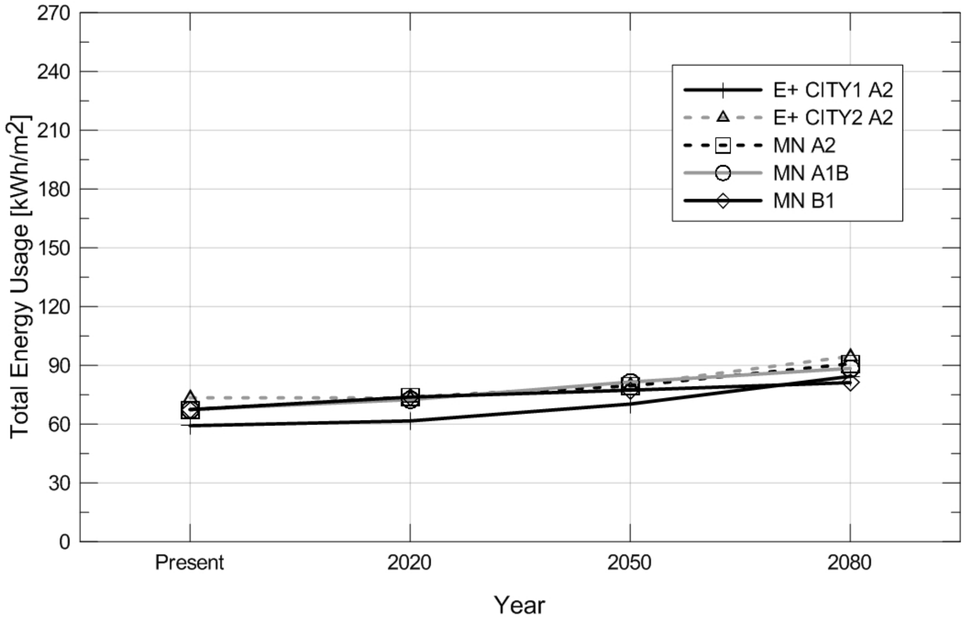


Figure 6.7: Athens: total energy usage calculated from different weather files.

Generic latitude	Station (city)	Country	Annual average Temperature
37°	Athens	Greece	18.2
41°	Barcelona	Spain	15.6
45°	Turin	Italy	11.6
48°	Paris	France	11.5
51°	London Gatwick	UK	9.6
55°	Copenhagen	Denmark	8.0
59°	Stockholm	Sweden	6.7

Table 6.1: Average annual temperatures referring to the city at each latitude.

the same latitude and differ by 2.45° in terms of longitude. London and Oostende are also quite close for both longitude and latitude with a difference of 3.05° and 0.05° respectively. Stockholm, which seems to have the most similar sets of data referring to different sources, is quite distant from Karlstad. They are separated by 4.48° of longitude and 0.28° of latitude.

We can argue that there is not a strict correlation between latitude, longitude and the climate conditions. In fact, according to their vicinity, Turin and Caselle should have had the closest energy results, but it does not occur. Moreover, Stockholm and Karlstad have more similar energy usage than Athens and Andravida even if the former pair is further apart the latter pair.

In conclusion, the closer the cities are in terms of latitude (and longitude), the better it is in general, but the same latitude and a quite similar longitude are not a good representation of the same climatic area. Anyway, different cities at the same latitude cannot be considered as being in the same climate zone. There are many other factors which influence the local climate and that are difficult to predict (e.g., humidity, precipitation, sea influence, urban heat island).

In the following analysis we will consider only one city for each latitude, eliminating the results coming from E+ CITY1. Table 6.1 summarizes the latitudes, the remaining cities and the average annual temperatures[1].

6.2 Robustness Comparison

The base case and the seven refurbishment cases representative of each group are compared at different latitude with the box-whiskers plot.

Figure 6.8 shows the total energy usage for the base case. Without any renovations, the building model is most robust in Turin and Athens, and worst in Stockholm and Copenhagen. The lowest energy usage is recorded in Barcelona. In general, the most sensitivity to climate change is recorded in colder climates. For this reason, the base case in Stockholm and Copenhagen is less robust than in the other cities. At lower latitudes, hence hotter climates, there seems not to be a strong correlation between energy usage and robustness.

Figure 6.9 illustrates the energy usage for the external insulation of the wall. It shows a lower energy usage for all the cities but almost the same width of boxes and whiskers, hence energy range. The width of the boxes seems to be smaller than for the base case, but the graph is not enough to estimate the difference. Also the medians seem to have the same position, besides for Turin where it almost disappear in the first quartile showing a low-skewed distribution of data. In the base case the building model behaves better in Copenhagen instead of Stockholm, whereas with the external

[1]source: www.climatedata.eu

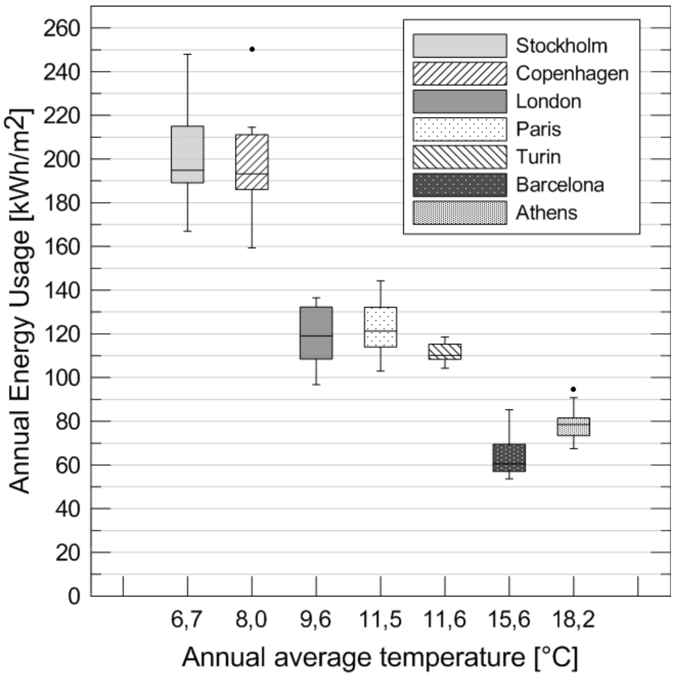


Figure 6.8: Annual final energy usage for heating and cooling for the base case (BC0).

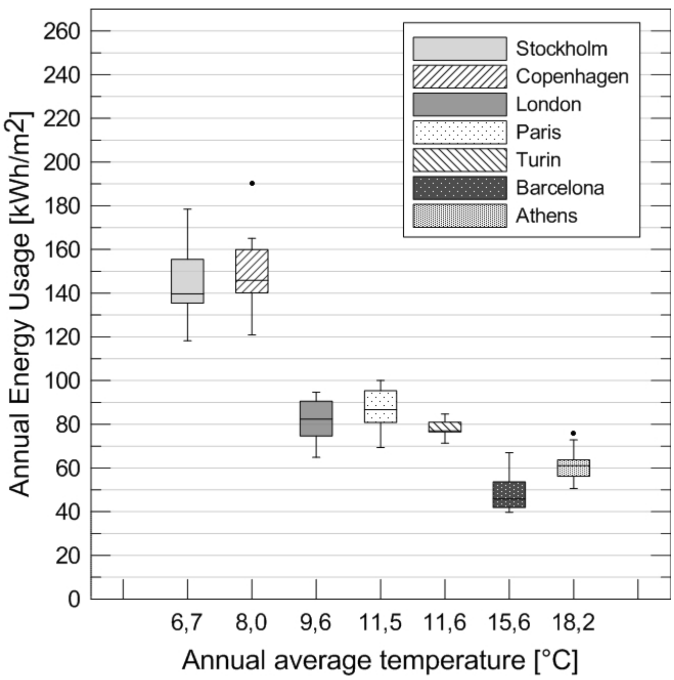


Figure 6.9: Annual final energy usage for heating and cooling for the external insulation of the wall (RC3).

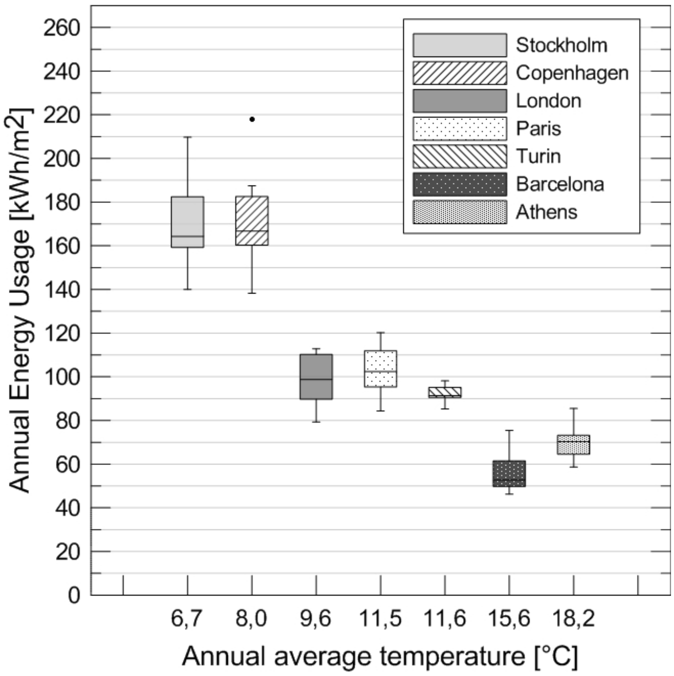


Figure 6.10: Annual final energy usage for heating and cooling for the external insulation of the roof (RC9).

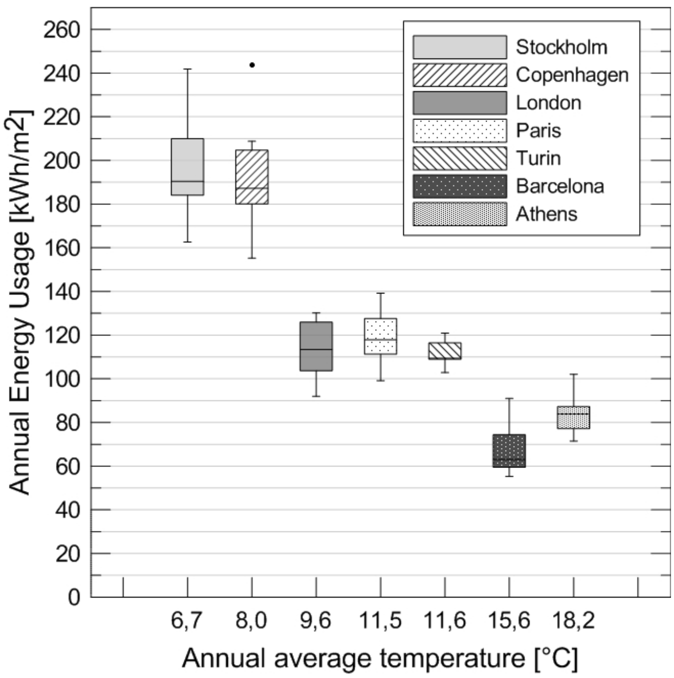


Figure 6.11: Annual final energy usage for heating and cooling for the insulation of the floor (RC15).

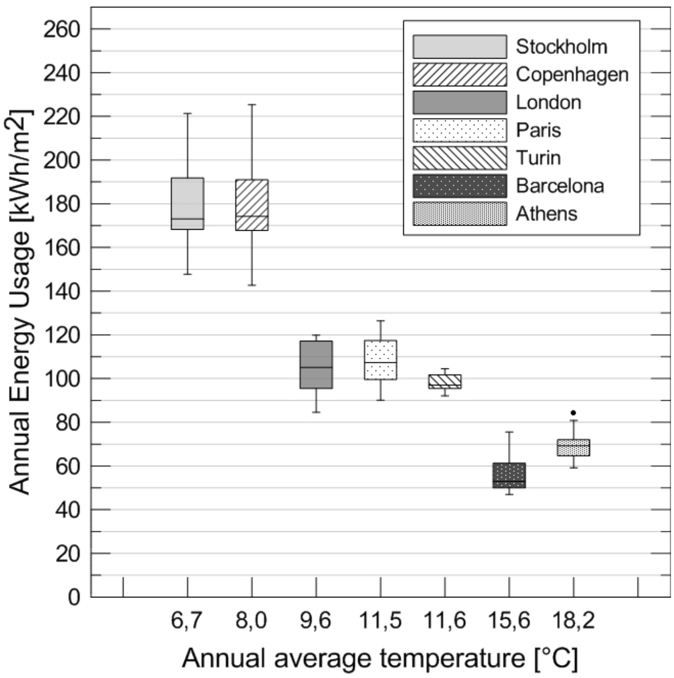


Figure 6.12: Annual final energy usage for heating and cooling for use of triple glazing with argon (RC18).

insulation of the wall the building has a smaller range of energy usage in Stockholm compared to Copenhagen.

Figure 6.10 shows the energy ranges for the insulation of the roof. The energy consumption values are higher compared to the external insulation of the wall but the robustness seems to be the same or slightly lower.

Figure 6.11 illustrates the robustness for the insulation of the floor, which is almost the same as the one of the base case.

Figure 6.12 shows the energy usage ranges for the use of triple glazing with argon. Also in this case, the ranking between the seven cities is the same in terms of both energy usage and robustness. In Turin the refurbishment behaves in a better way considering the robustness, whereas in Barcelona the same thermal model consumes less total energy. Stockholm and Copenhagen are still the worst cities for both robustness and energy consumption.

Figure 6.13 illustrates the use of external shading systems and figure 6.14 the use of PCM. No relevant changes can be seen in these graphs in comparison with the others.

On the other hand, figure 6.15 shows the most relevant variations of robustness and energy usage. The increase of the airtightness, beside decreasing the energy usage at all the latitudes, present shorter boxes for almost all the cities. It must be noticed that all the boxes are smaller in comparison with the other refurbishments, beside for Turin and for Athens. At these latitudes, in fact, an increase of the airtightness seems

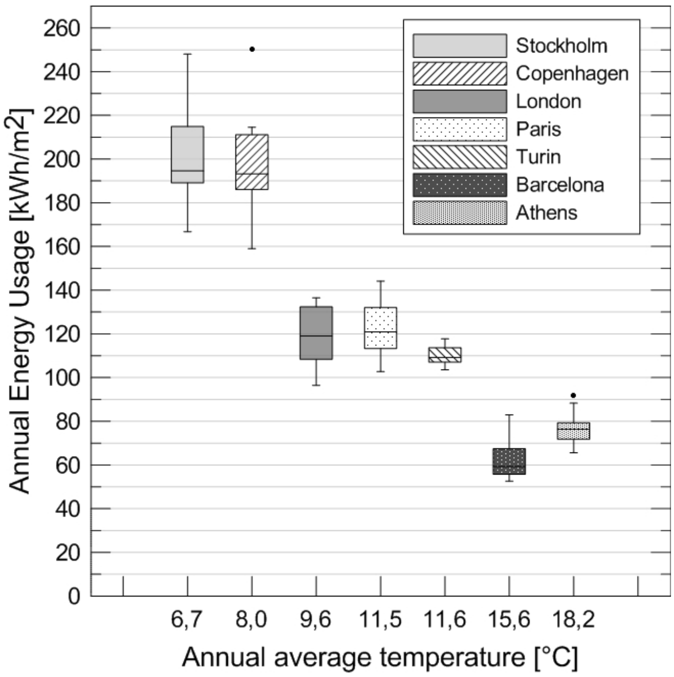


Figure 6.13: Annual final energy usage for heating and cooling for use of external shading systems (RC20).

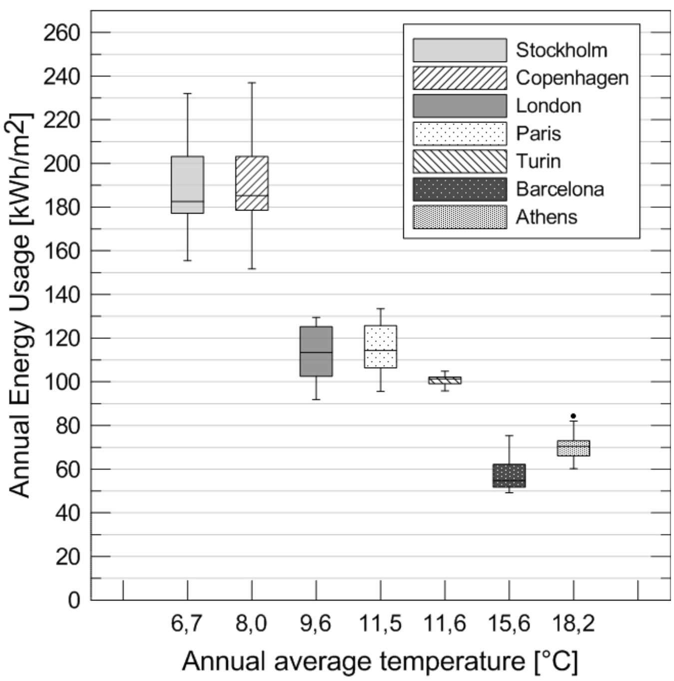


Figure 6.14: Annual final energy usage for heating and cooling for use of PCM (RC21).

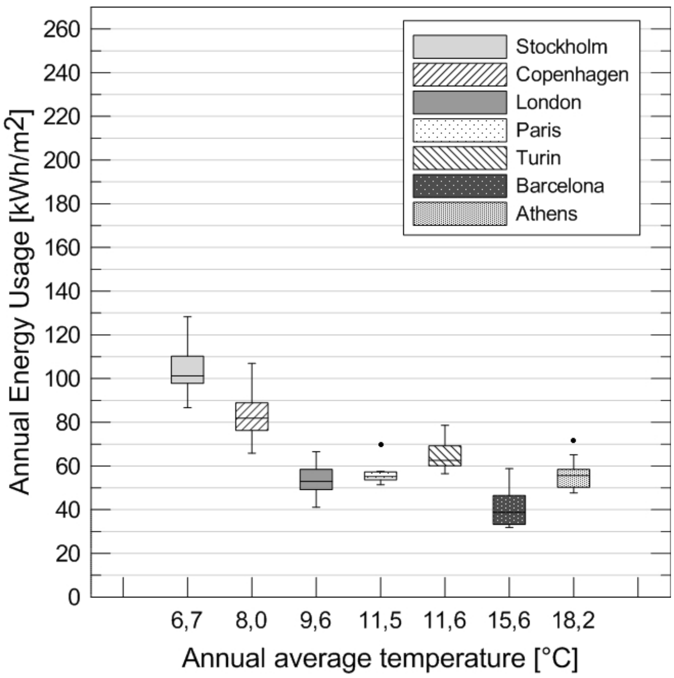


Figure 6.15: Annual final energy usage for heating and cooling for the increase of the airtightness (RC22).

to have a more negative effect in comparison with the other latitudes. In particular, the boxes of Stockholm, Copenhagen and London have almost the same dimensions of the one of Barcelona, showing a big increase in the robustness in comparison with the base case and the other refurbishment cases. Paris shows the biggest change in terms of robustness presenting a very small box and almost no whiskers.

In conclusion:

- Each refurbishment has a different robustness at different latitudes.
- In almost all the cases (beside the airtightness improvement, RC22) the robustness in terms of energy usage is much higher at lower latitudes.
- The variation of robustness through latitudes is almost the same for each refurbishment. The boxes have almost the same dimension and are just shifted higher or lower.
- The biggest changes are recorded for the airtightness solution. In this case, in fact, the building behave almost in a similar way in different cities as can be seen by looking at the dimension of the boxes.
- RC22 (airtightness improvement) is the most robust solution in terms of variation in time (dimension of a single box) and in space (similar dimensions of all the boxes at different latitudes).

- The energy performance are more influenced by the climatic variations than by the refurbishment measures, beside for the increase of airtightness.
- The different behaviour of only the RC22 is due to the fact that is the only measure that behaves in a non-linear way. The crack template of the model, in fact, takes into account the differences in air pressure and wind speed at each latitudes instead of the temperatures as in the other refurbishments.

6.3 Energy Saving Comparison

The energy saving comparison illustrates the ranges of energy difference in four years (present, 2020's, 2050's and 2080's) between the refurbishment cases and the base case at present. The formula used are the following:

$$\Delta E_p = E_{BC_p} - E_{RC_p} \tag{6.1}$$

$$\Delta E_{20} = E_{BC_p} - E_{RC_{20}} \tag{6.2}$$

$$\Delta E_{50} = E_{BC_p} - E_{RC_{50}} \tag{6.3}$$

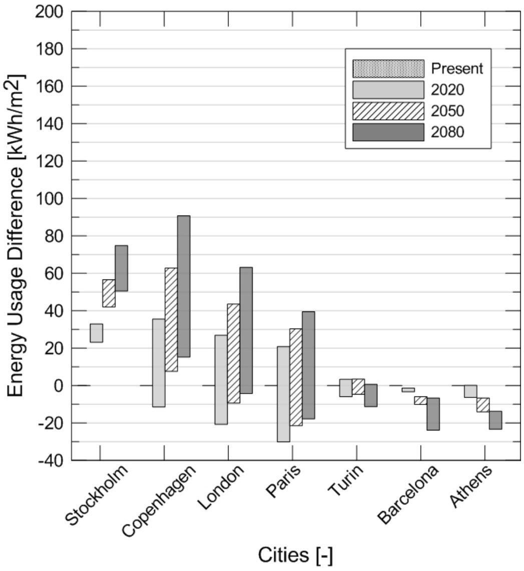
$$\Delta E_{80} = E_{BC_p} - E_{RC_{80}} \tag{6.4}$$

where:
- p refers to the present
- 20, 50, 80 refers to 2020's, 2050's and 2080's respectively
- BC refers to the Base-case
- RC refers to a general refurbishment case
- ΔE refers to the dimension of each bar.

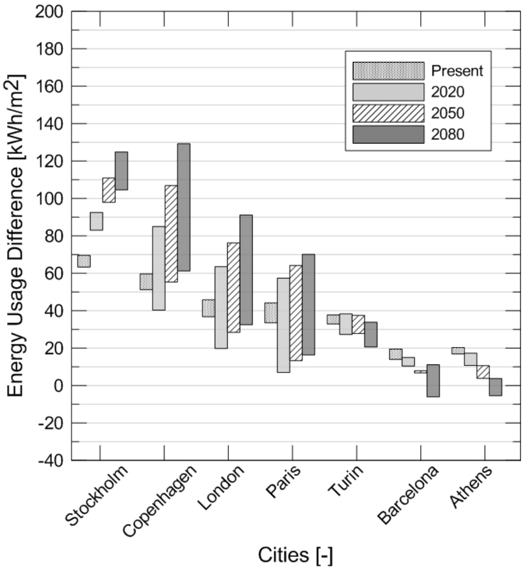
We used 18 weather files so each difference refers to the same weather file. In the graph, the boxes are calculated on the basis of the maximum and minimum value in the distribution of results.

In this analysis,"better" values should show higher magnitudes on the y-axis (i.e. higher bars), while the size of each bar on the y-axis should be small as well.

Figure 6.16a shows the comparison between the base case in future years and the base case at present. For this reason the first floating bars referring to the present are always null (i.e. no renovation and no change of weather file). Without any kind of renovation, the same building behaves in very different ways at the seven latitudes. In particular, the width of the floating bars is smaller for Turin, Barcelona and Athens, followed by Stockholm and then Paris, London and Copenhagen. It seems there are no correlations between the annual average temperature and the performance of the

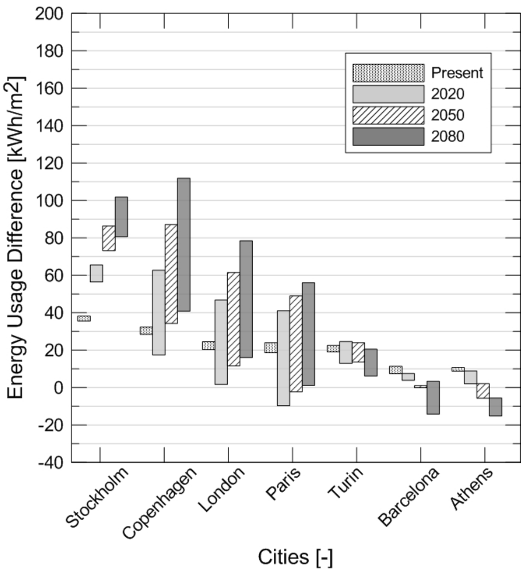


(a) Base case (BC0).

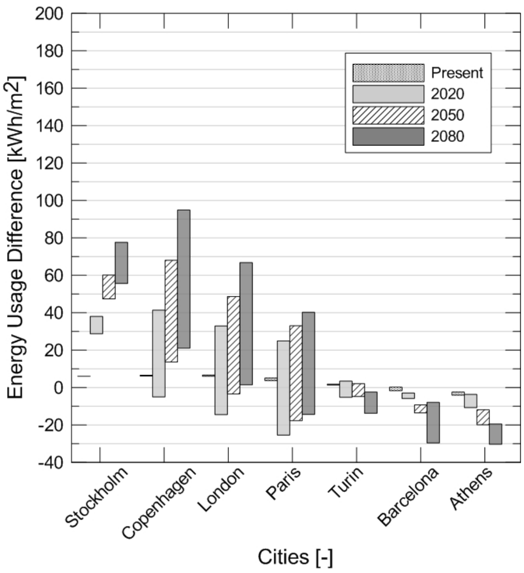


(b) External insulation of the wall (RC3).

Figure 6.16: Annual final energy usage difference between base case at present and the base case/refurbishment in present and future years.

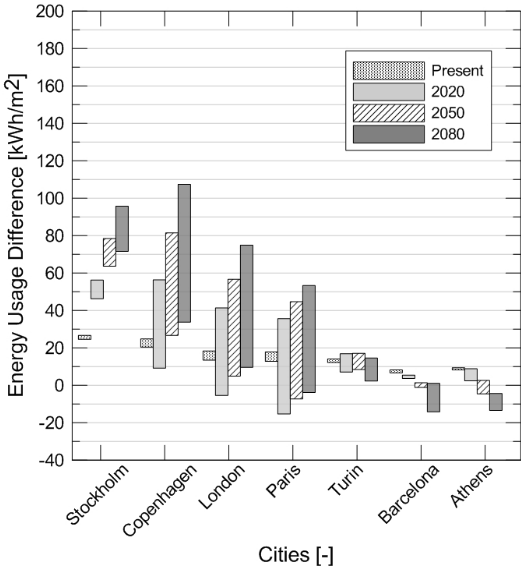


(a) External insulation of the roof (RC9).

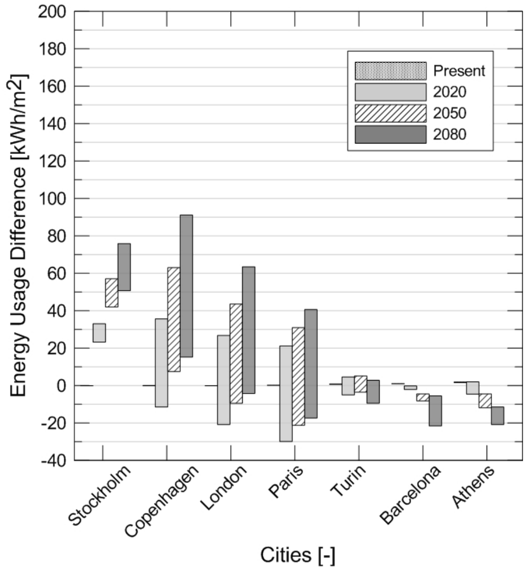


(b) Insulation of the floor (RC15).

Figure 6.17: Annual final energy usage difference between base case at present and the base case/refurbishment in present and future years.

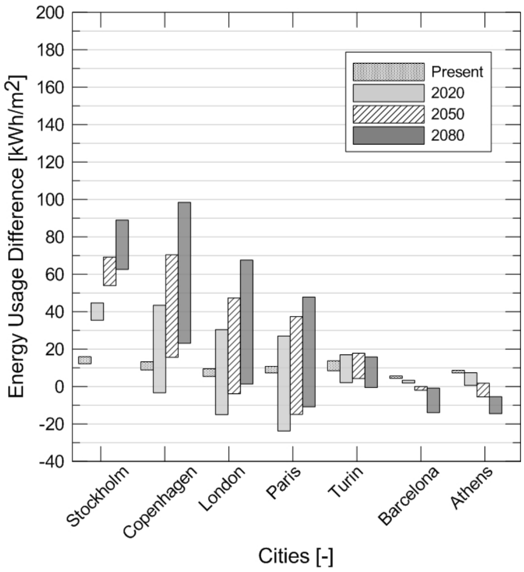


(a) Use of triple glazing with argon (RC18).

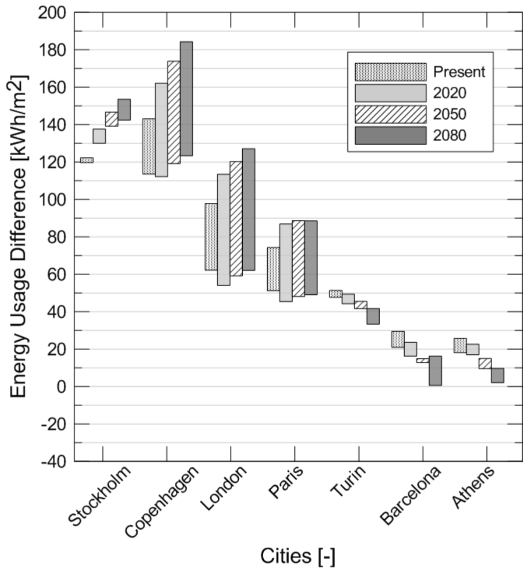


(b) Use of external shading systems (RC20).

Figure 6.18: Annual final energy usage difference between base case at present and the base case/refurbishment in present and future years.



(a) Use of PCM (RC21).



(b) Increase of the airtightness (RC22).

Figure 6.19: Annual final energy usage difference between base case at present and the base case/refurbishment in present and future years.

building. In fact, in Paris and Turin, which have almost the same average annual temperature, the building model has very different ranges of change of energy usage. Moreover, Stockholm presents smaller energy ranges in comparison with Copenhagen, London and Paris even if it is the coldest city. It is important to notice that at high latitudes (hence colder climate), the energy saving is higher in 2080, whereas in southern Europe there is an opposite trend. This fact means that, without any intervention, buildings in the future will consume more than today at low latitudes and less than today at high latitudes. This is due to the fact that the global warming will lead to higher energy consumption for cooling in the hot regions, but will temper the cold climate reducing the energy usage for heating. This seems to be in line with intuition.

The further out one goes in the future, the more uncertain predictions become and this is shown by the bigger bars in 2080's in comparison with the other years. In general it is difficult to find a correlation between latitudes and energy saving. By looking at the base case it can be argued that climate change will bring better results in Stockholm. At this latitude, in fact, the energy saving is one of the highest among the other cities and the range is small. Only in Copenhagen there is more energy saving but the ranges, hence the uncertainties, are much bigger than for Stockholm. Barcelona and Athens are comparable in terms of both energy difference and variations. The width of their bars is quite similar in all the years (Barcelona has a smaller bar for 2020 and a bigger one for 2080) and they record negative difference, in other words more energy consumption in the future compared to today.

By looking at the floating bar charts of the other refurbishments it can be noticed that the width and the mutual position of the bars is almost the same beside some little variations that are difficult to estimate. The ranges referring to the present are always the smallest ones because there are less uncertainties related to the climate compared to the future years. For Copenhagen, London and Paris the difference between the ranges in the present and in the future years are very relevant. For example, figure 6.17a shows that in Paris the energy saving of a house with roof insulation in comparison with the not-refurbished one is positive at current days but it becomes negative in 2020. Moreover the uncertainties over the amount of energy saving are very relevant.

The only refurbishment that shows differences in comparison with the others is the RC22, the increase of the airtightness. Figure 6.19b shows that the energy saving is higher for all the latitudes. Another difference for this refurbishment can be seen in the ranges at present, which are bigger than the other refurbishments. This solution is the only one that leads to energy saving in the future also at lower latitudes, i.e., in Barcelona and Athens. Stockholm is still the best place in terms of both high energy saving and small ranges variation.

6.4 Overall Comparison

To conclude the analysis it is necessary to sum up the information coming from the box-whiskers plots and from the floating bar charts. We calculate the RI and the ESI referring to the total energy usage, hence to the same data plotted before. Then we summarize the two results with the GI by giving the same weight to the two indices. In this way the GI is the average between the RI and the ESI. We plotted the three indices for each refurbishment in such a way to compare them.

Figure 6.20a shows the results for the external insulation of the wall. In general, the ESI is higher than the RI. Moreover, the three indices have almost the same value for Stockholm, Copenhagen, Paris and Turin but not for London and even more different values for Barcelona and Athens. For the last two cities it is possible to see that the RI is almost equal to zero. This is due to the fact that the indices are normalized with the base case. In this case, in fact, the RC3 has a small range but its range is almost similar to the one of the base case. In other words, the refurbishment does not add much more benefits to the base case. By looking at figure 6.20a is possible to see that the external wall insulation, in terms of GI, behaves in a better way in Turin and in the worst way in Athens.

The same conclusion can be done for the refurbishment of the roof (RC9, figure 6.20b) but in this case, in Turin, the RI is higher than the ESI.

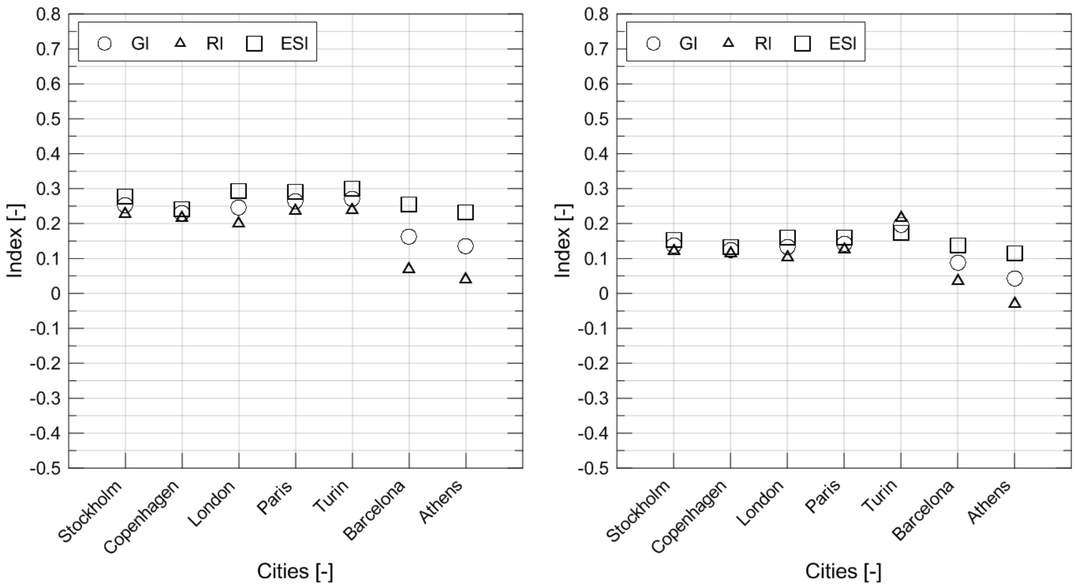
Figure 6.21a shows the indices for the insulation of the floor. Paris is the city where this solution has more benefits in terms of both energy saving and robustness to climate change. Athens is still the place where the refurbishment behaves in the worst way.

Figure 6.21b indicates the indices for the use of triple glazing with argon. Almost all the values are around the 0.1 and both RI and ESI are similar for all the cities beside for Paris, where the ESI is slightly better than the RI.

Figure 6.22a shows that the indices for the use of external shading are almost always zero. Only in hotter regions such as Turin, Barcelona and Athens it makes a little difference in comparison with the base case.

Figure 6.22b indicates very different results for the three indices at the seven latitudes. In particular, the case of Turin is the most relevant. It shows that the RI is very high and that the ESI is comparable with the other cities. All the other latitudes indicates an higher ESI value in comparison with the RI, beside Barcelona.

Figure 6.23 shows that the airtightness solution behaves in the most different way compared with the other refurbishments. Also in this case the three indices have very different values in Turin. The RI is very low and the ESI has almost the same positive value so that their average (the GI) is closer to zero. A very low RI number indicates that the refurbishment solution is less robust than the base case. On the contrary, a positive ESI states that the refurbished model saves more energy than the base case one. By looking at the GI, the RC22 refurbishment has a better energy performance in Paris



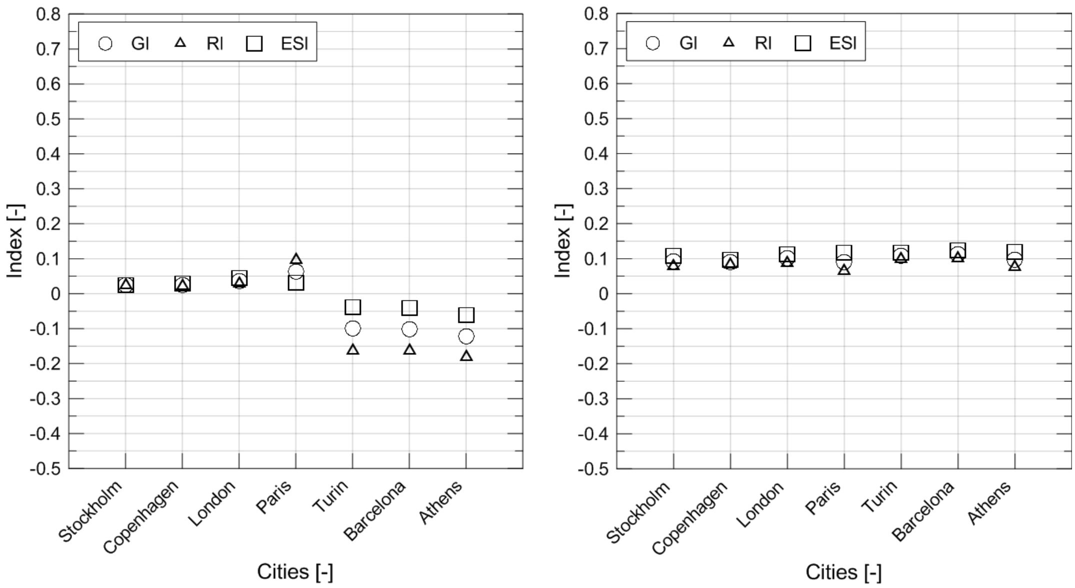
(a) External insulation of the wall (RC3). **(b)** External insulation of the roof (RC9).

Figure 6.20: RI, ESI and GI for the sum of heating and cooling.

and a bad one in Turin. The indices referring to RC22 are the most unequal due to the fact that for both robustness and energy saving, the differences between refurbished cases and base case are different in each city. In all the other cases, in fact, the graphs seem just shifted in comparison with the base case. Due to the fact that all the indices are normalized with respect to the base case, their values are very similar throughout the cities.

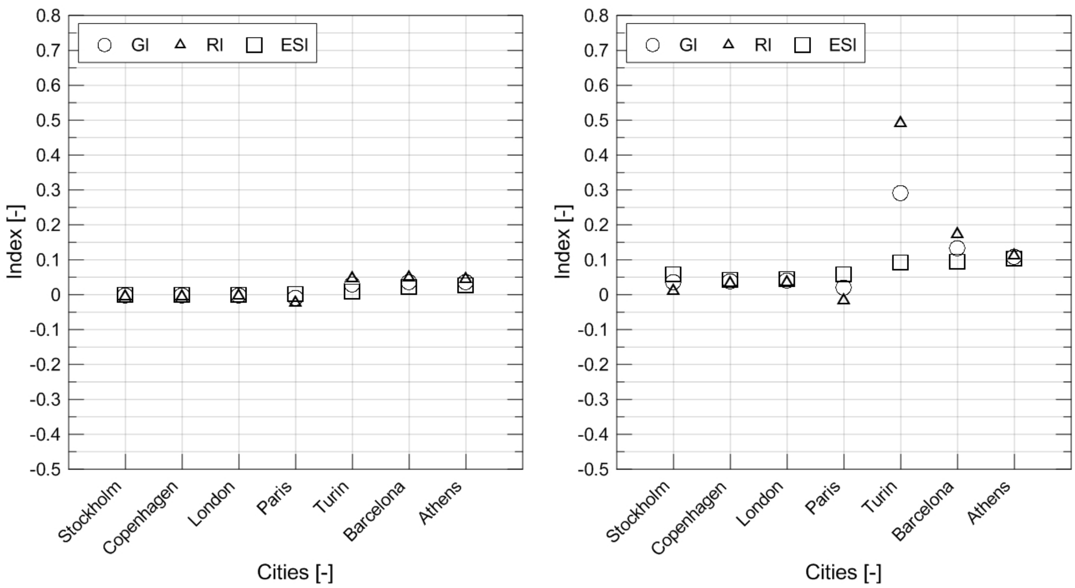
Some general conclusions of the comparison between the cities are:

- The airtightness refurbishment (RC22) is the solution which behaves in a better way at all latitudes, followed by the external insulation of the wall (RC3).
- Almost all the refurbishments behave in a better way in terms of energy saving, instead of robustness, with some exceptions (i.e., RC9, RC20 and RC21 in Turin, RC22 in Stockholm, RC20 and RC21 in Barcelona and RC15 in Paris).
- If the RI, ESI and GI indicate almost the same value, it means that the graph referring to a refurbishment case is shifted in comparison to the base case. In other words, the difference between the refurbishment cases and the base case are the same at different latitudes.
- The non-linear behaviour of the indices for the increase of airtightness (RC22) means that the model react in a non-linear way to climate change, by taking into account the differences of wind speed and pressure.
- The most different behaviour between RI and ESI –hence between the robustness



(a) Insulation of the floor (RC15). **(b)** Use of triple glazing with argon (RC18).

Figure 6.21: RI, ESI and GI for the sum of heating and cooling.



(a) Use of external shading systems (RC20). **(b)** Use of PCM (RC21).

Figure 6.22: RI, ESI and GI for the sum of heating and cooling.

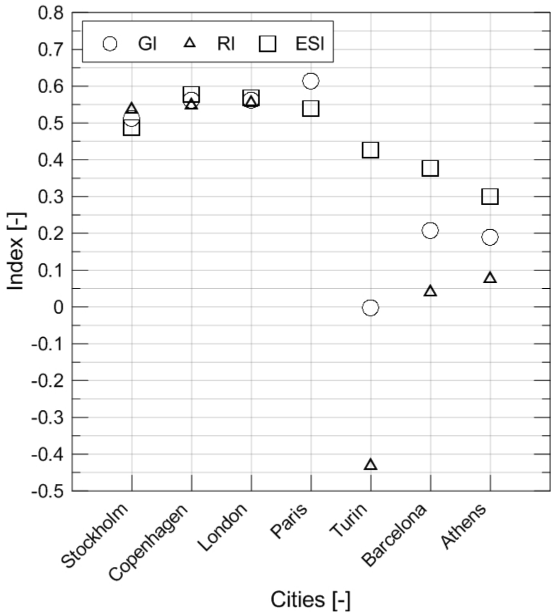


Figure 6.23: RI, ESI and GI for heating and cooling for the increase of the airtightness (RC22).

and the energy saving– is present at lower latitudes. In particular, in Turin, Barcelona and Athens the energy saving is higher than the robustness of different solutions in comparison with the base case. This is due to the fact that the energy saving variation is smaller compared to other latitudes, but the refurbishment solutions do not improve upon the base case in terms of robustness.

- The most robust refurbishments among different climate are the use of triple glazing with argon (RC18) and the use of external shading systems (RC20). Anyway, this latter is not the best solution to adopt at all latitudes, in fact it behaves almost in the same way as the base case. Hence its indices are constant between latitudes but closer to zero.

Chapter 7

Conclusions

The building sector uses about one-third of all the raw materials and energy produced in Europe and over half of the electricity. Energy consumption can be reduced improving the thermal properties of the existing building stock, given its age profile and the current European housing market. This way (while maintaining an optimum indoor environment), it is possible to minimize dependency on conventional fuel sources and reduce the environmental impact from fossil fuel usage.

Focusing on refurbishment strategies applied retrospectively to an existing residential dwelling, it is necessary to evaluate which one performs better in terms of energy usage. Engineers and architects simulating building performance must be aware of the wide range of uncertainties related to climate change in future years, hence to the uncertainties of weather files used to describe it. Decisions regarding thermal or bioclimatic features of buildings must be considered in light of these climate alterations and uncertainties, with respect to the impossibility of knowing them precisely. The climate in the next years, in fact, could be quite different from a simple extrapolation of the present one. Since we do not know which future will happen yet, we need to use robust strategies, which will work reasonably well no matter what the future will bring.

We proposed a methodology to systematically evaluate strategies robust to the threat of climate change and to discover which solutions perform similarly in terms of energy usage under many possible future climates. A robust solution works well even in scenarios where the limits of various uncertain variables are realised, in this case related to climate change. To reach this goal, it is indispensable to include in building simulations many possible weather files and so the many probable future climates associated with them. Results may be more helpful when treated as being probabilistic instead of deterministic as they are today, and if they show ranges of data instead of single values.

The results from the energy simulations we analysed highlight the sensitivity of different refurbishment strategies to alternative future climates simulated in different years, scenarios and latitudes, using different sources. In particular, the energy performances produced with simulations run with files from various sources and scenarios are considerably different although the ranking of each refurbishment solution does not change in the majority of the cases. This is most likely due to the fact that temperature is morphed [1] but solar radiation is kept the same in the future. *The first outcome of our study is that, in terms of energy performance, climate change uncertainties related to the weather files are unlikely to affect which measures behave in a better way in present and future years.* The methodology developed is important to identify ranges of possible energy performance behaviour instead of producing a single output data point, thus identifying robust solutions. The RI is used to numerically quantify the data shown in the box-whiskers plot and the ESI completes the assessment in terms of energy saving. The GI can be calculated in different ways, according to the importance given to robustness or to energy saving. *The second outcome is that rankings developed on the basis of heating or cooling energy usage are completely different. In fact, the ability of a particular solution to reduce heating energy usage is not necessarily correlated to the capability to reduce the need of cooling energy.* The two energy usage terms must be summed to have a complete description of the annual energy performance of a solution. In the comparison between latitudes, it is possible to notice that total energy usage is more influenced by the heating part in cold climates and by the cooling part in hot climates, which is intuitive.

A general conclusion of our work is that the assessment of different design strategies seems incomplete with only current weather data, without taking into account future climate change. Due to climate uncertainties it is necessary to include more input weather files in building energy simulations of future years. Only in this way could design strategies for policy – and decision – makers be more reliable.

Mahatma Gandhi said that "the future depends on what you do today". For performance-based building design, however, it can be argued that what you do today depends on the future.

Further Work

The methodology could be applied to study more refurbishments. In particular active measures should be assessed as well. The combination of more strategies could be implemented. Moreover, the methodology could be applied to new dwellings and to non-residential buildings.

The graphs and the indices are based on descriptive statistics. A bigger sample of input weather file and therefore of energy usage could lead to better approximation of the population distribution. More input weather files could include other future

[1] Morphing method: method to down-scale the monthly changes to hourly changes and then apply the changes to the current weather data to stochastically generate future weather data and adjustment of present-day weather data with regional climate change model predictions (Belcher et al. 2005).

scenarios, years and refer to different sources.

Another improvement in the methodology is the inclusion of occupants' behaviour. In particular, the concept of thermal adaptation could change the results significantly. Our methodology has been developed to provide a fixed temperature inside dwellings in both summer and winter. By letting indoor temperature vary, final energy usage will definitely change.

seeing the work of Tian and de Wilde (2011), a method like ours can be validated with the use of one or more sensitivity analysis methods. The indices should be tested further to see if they correctly describe the performance of buildings.

A methodology to describe the overlapping of the box-plots should be implemented. In particular, it would be useful to know the probability of finding a particular energy usage result in the range of results overlapping with the base case.

The methodology is currently implemented with the use of Matlab and Excel. A GUI could be developed to make the process easier and available for professionals that want to use it. The input files would be the model (.idf) and the weather files (.epw) and the output files would be the graphs (box-whiskers plot and floating bar chart), and the three indices.

Appendix

Energy Performance Evaluation

In the following part we explain a simplified description of thermal simulation based on standard ISO 13790. In particular, in the cold season, the building's *heating need* is a relationship between heat losses (transmission and ventilation) and heat gains (internal and solar). A reduction factor is used for the heat gain. The calculation method for the energy consumption for space heating and for each calculation period (month or season) is based on the following equation:

$$Q_H = Q_{loss} - \eta_{H,gn} \cdot Q_{gains} \tag{7.1}$$

where:
Q_H is the building energy need for heating
Q_{loss} is the total heat transfer losses (transmission and ventilation)
Q_{gains} accounts for heat gain (internal and solar)
$\eta_{H,gn}$ is the dimensionless gain utilisation factor.

In the same way, the building *cooling need* is a relationship between heat losses (transmission and ventilation) and heat gains (internal and solar), but this time the reduction factor refers to the heat losses. The calculation method for the energy need for space cooling and for each calculation period (month or season) is based on the following equation:

$$Q_C = Q_{gains} - \eta_{C,gn} \cdot Q_{loss} \tag{7.2}$$

where:
Q_C is the building energy need for cooling
Q_{loss} is the total heat transfer losses (transmission and ventilation)
Q_{gains} accounts for heat gain (internal and solar)
$\eta_{C,gn}$ is the dimensionless utilisation factor for heat losses.

Heat losses are calculated with the sum of the total heat transfer by transmission (Q_{tr}) and ventilation (Q_{ve}), by the following equation:

$$Q_{loss} = Q_{tr} + Q_{ve} = (H_T + H_v) \cdot (\Theta_i - \Theta_e) \cdot t \tag{7.3}$$

where:

- Θ_i is the internal set-point temperature
- Θ_e is the average external temperature during the calculation period
- t is the length of the calculation period
- H_T is the heat loss transmission coefficient, through the envelope elements, calculated by the relation

  $$H_T = \sum A_i U_i + \sum l_k \psi_k + \sum x_j \tag{7.4}$$

  where:

  A_i is the area of element i of the building envelope (m^2)

  U_i is the thermal transmittance of element i of the building envelope($\frac{W}{Km^2}$)

  l_k is the length of linear thermal bridge k (m)

  ψ_k is the linear thermal transmittance of thermal bridge k ($\frac{W}{Km}$)

  x_j is the point thermal transmittance of point thermal bridge j

- H_v is the heat transfer coefficient by ventilation, calculated by the equation:

  $$H_v = \varrho_a c_a q_{ve} \tag{7.5}$$

  where:

  q_{ve} is the air flow rate through the building, related to air change rate (n) and conditioned space volume (V)

  $\varrho_a c_a$ is the heat capacity of air per volume, equals to 1200 $\frac{J}{Km^3}$

Heat gains are calculated summing up the internal gains (Q_{int}) and the solar gains (Q_{sol}), with the following equation:

$$Q_{gains} = Q_{int} + Q_{sol} \tag{7.6}$$

The two terms of the equations are calculated with:

- the internal heat gains during the considered month or season. They are a result from the metabolic gains from occupants, power consumptions and therefore heat from appliances and lighting devices. They are calculated with the following equation:
$$Q_{int} = \{\sum \Phi_{int,mn,k}\} \cdot t + \{\sum (1 - b_l)\Phi_{int,mn,u,l}\} \cdot t \tag{7.7}$$

  where:

  b_l is the reduction factor for the adjacent unconditioned space with internal heat source l, defined in ISO/DIS 13789:2005

  $\Phi_{int,mn,k}$ is the time-average heat flow rate from internal heat source k (W)

  $\Phi_{int,mn,u,l}$ is the time-average heat flow rate from internal heat source l in the adjacent unconditioned space (W)

  t is the length of the considered month or season

- the solar heat gains during the considered month or season are a function of local sunshine (I) and the solar transmission (SHGC of glass, transparent covering, transparent insulation) and absorption characteristics of window panes. They are calculated with the following equation:
$$Q_{sol} = \{\sum \Phi_{sol,mn,k}\} \cdot t + \{\sum (1 - b_l)\Phi_{sol,mn,u,l}\} \cdot t \tag{7.8}$$

  where:

  $\Phi_{sol,mn,k}$ is the time-average heat flow rate from solar heat source k, (W)

  $\Phi_{sol,mn,u,l}$ is the time-average heat flow rate from solar heat source l in the adjacent unconditioned space (W)

File Nomenclature

In order to recognize each weather file with its features, we called the .epw files in a similar way:

$$CITY2\_SOURCE\_SCENARIO\_YEAR$$

$CITY2$ refers to the name of the city which is present in the data obtained with both Meteonorm and the U.S. Department of Energy website (cf. Figure 4.5. The acronyms used for each city are:

- ATH = Athens
- BAR = Barcelona
- TOR = Turin

- PAR = Paris
- LON = London
- COP = Copenhagen
- STO = Stockholm

SOURCE specifies if the weather file comes from Meteonorm (Met) or from the U.S. Department of Energy website (IWEC or IGDG). For all the cities, beside Caselle, the two weather files from the website come from the IWEC source. For this reason the second part of the code identify the city to which the weather file refers. These are the acronyms used for each "twin" city:

- ANDR = Andravida
- BPOR = Porto
- IGDG = Caselle
- BRES = Brest
- LOOS = Oostende
- COBA = Oban
- CARL = Karlstad

The names are given in such a way to arrange the files from the website before the ones from Meteonorm in an alphabetical order. In this way, the elaboration of the data is easier.

SCENARIO identifies the future scenario to which the file refers. *A* refers to present files.

YEAR specifies the year of the specific climate condition of the weather file. The term *pres* refers to the current climate.

An example of the nomenclature of the files is shown in figure 7.1.

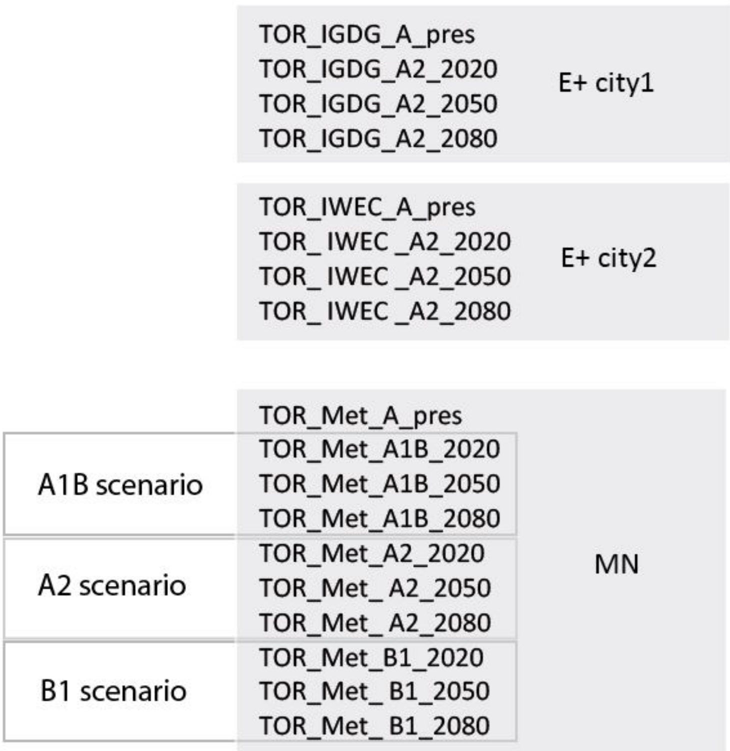


Figure 7.1: Files nomenclature for Turin and Caselle.

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